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Evaluation of Ventilation Requirements and Energy Consumption in Existing New York City School Buildings

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Stanley T. Liu, Charles M. Hunt,
and Frank J. Powell

Center for Building Technology
Institute for Applied Technology
National Bureau of Standards
Washington, D.C. 20234

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ABSTRACT

A study was made, under the sponsorship of the National Science Foundation and in collaboration with the New York City Board of Education, of the energy consumption and ventilation requirements of typical existing urban public schools, for the purpose of determining the pattern of energy usage in such public schools so that effective energy conservation measures can be taken both for existing schools and for future new school design.

Electricity and fuel-oil consumption data from May 1970 through April 1973 on 19 existing schools provided by the New York City Board of Education were analyzed. Analysis showed that the overall energy consumption of 17 of the 19 schools varied by a factor of less than 2. Average yearly consumptions per 1,000 ft^2 (92.9 m^2) gross floor area of 5,250 kWh of electrical energy and 417 gallons of No. 6 fuel oil (2.03×10^8 J and 0.017 m^3 per m^2 of gross floor area), were selected as a norm typical of the existing schools. These figures correspond to 82,400 Btu/year-(gross) ft^2 (29.7 W/m^2) at the building line or an estimated 126,000 Btu/year-(gross) ft^2 (45.4 W/m^2) when calculated in terms of raw fuel at the generating plant. The figures can be used for future comparison purposes with a new energy conservation school. A computerized thermal energy simulation, using the program NBSLD, was performed on one of the schools having an energy consumption close to the norm. The results showed good agreement between the predicted and measured monthly electricity and fuel-oil consumption data. Detailed analysis of the pattern of energy consumption showed that 75 percent of the thermal energy during the heating season was used for the heating of outdoor air for ventilation purposes, and 80 percent of the electrical energy was used for lighting.

A ventilation test was conducted over a 4-day period in a typical classroom. It was found that a reduction of the air change rate from the normal 4.6 changes per hour to 1.3 changes per hour did not significantly change the indoor environment as expressed in terms of temperature, relative humidity, oxygen content level, and CO_2 concentration level. However, computation indicates that, when no mechanical ventilation was provided, the CO_2 concentration level would exceed the 0.5 percent safety limit, indicating that natural air infiltration alone will not provide adequate ventilation for the general health and safety of the students.

Key Words: CO_2 concentration; computerized thermal simulation; energy conservation in schools; energy consumption; energy utilization in schools; oxygen content; reduced ventilation rate; school operation schedule; ventilation test

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1. Introduction

Numerous articles and detailed research studies[1, 2, 3/*] indicate that the nation continues to face increasing demands for fuel and electrical energy which in turn impose great pressures on available supplies. This situation, coupled with air and thermal pollution problems of the nation, caused leaders to declare that conservation of energy resources is of paramount importance in government and industry.

Energy used in buildings for space heating and cooling, lighting, hot water heating, and mechanical ventilation constitutes a large portion (32 percent) of energy consumption in the United States, as was recently documented by a Stanford Research Institute report[3/]. It is estimated that at least 10 to 20 percent, and maybe as high as 40 to 50 percent[4/] of energy used in buildings could be saved in the design and construction of new buildings by a comprehensive thermal analysis in the design of the building envelope, by a more careful evaluation of fresh air ventilation requirements and lighting requirements, and by the utilization of efficient energy conversion equipment.

Public school buildings, as a group, constitute a significant portion of the public buildings in the cities of the United States. The Center for Building Technology of the National Bureau of Standards, under the sponsorship of the National Science Foundation, and with the collaboration of the Board of Education of New York City, undertook a study in 1974 on the pattern of energy consumption, and the effect of ventilation on a classroom environment, in a typical urban public school. The purpose was to obtain detailed information on the energy usage of school buildings in order to develop guidelines for energy conservation in the design and construction of future energy-efficient school buildings. This report presents the results of this study.

Work done at NBS on this project consisted of two parts. The first part involved (1) an analysis leading to the selection of a typical existing school in New York City to be used as a norm for comparison with a future new energy-conserving school, and (2) a detailed computer thermal analysis of the selected school using the NBS program called NBSLD[5/] to determine the breakdown of its energy usage with respect to lighting, heating, ventilation, and equipment operation, in order to identify the importance of the major areas of energy consumption in the new school design. The selection of a typical existing school as a norm was based on a study of the fuel-oil and electrical energy consumption data from May 1970 through April 1973, of 19 schools of varying size as supplied by the Board of Education of the City of New York. Field trips to five of the 19 schools were taken jointly with the Board of Education and its principal investigator, Richard Stein and Associates, to obtain a typical school schedule and operating data for various mechanical equipment. These data were then used as input to the NBS computer program for the thermal analysis.

The second part of this report gives the results of a one-week ventilation test conducted in a typical urban classroom in New York City to determine the effect of reduced ventilation on the interior environment, including the concentrations of carbon dioxide and oxygen, the change in dry-bulb temperature, the variation of relative humidity, and the activity and response of the students. These results are expected to provide information on the reduction of the rate of ventilation as a means of reducing the energy consumption.

Details of the above two parts of the project will be discussed in the following sections.

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* See references at end of text.

2. Energy Consumption of Selected Existing Intermediate and High Schools in New York City

2.1 Analysis of Energy Consumption Data

The electrical energy and fuel-oil consumption data for 19 schools on a monthly basis for 3 years (May 1970 - April 1973) were furnished by the Board of Education of New York City. These schools ranged in size from 160,000 to 400,000 square feet (14,860 to 37,160 m^2) of gross floor area and consisted of 6 intermediate schools and 13 high schools. A brief description of these schools is given in Table 1.

The numbering of the schools in Table 1 was chosen to correspond to increasing electrical energy consumption. From Table 1, it is seen that most of these schools are of the cavity-wall type construction (e.g., 4 inch (10.2 cm) brick, 2 inch (5.1 cm) airspace, 6 inch (15.2 cm) concrete block), 3 stories high, with a ceiling height ranging from 9 feet to 11 feet (2.7 to 3.4 m), and window to exterior wall area ratio of 0.40 to 0.50. Space heating is provided mostly by steam via perimeter fin-tube radiators located below the window sills. Most of the schools have no space cooling. Ventilation is provided by openable windows and roof-top exhaust fans with an exhaust rate of 560 cfm (0.26 m^3/s) per classroom. Classroom lighting is provided by fluorescent fixtures with an electric power consumption of 2.0 to 2.8 watt/ft^2 (21.5 to 30.1 W/m^2) floor area.

Data for the 3-year-averaged monthly electricity and fuel-oil consumption for the 19 schools are tabulated in Tables 2 and 3, and the 3-year-averaged yearly energy consumption data are plotted in Figures 1 to 3.

Figure 1 shows, in order of increasing amount, the yearly electrical energy consumption. It is seen that the variation in electrical energy consumption of the 19 schools is quite large, ranging from 3,600 kWh to 15,000 kWh per 1,000 ft^2 gross floor area (1.395×10^8 to 5.81×10^8 J/m^2). Howevei, by eliminating school No. 19, which is a windowless school with a high lighting level of 5.5 watt/ft^2 (59.1 W/m^2) of classroom area, the range for the remaining 18 schools is 3,600 to 8,700 kWh, with an average of 5,450 kWh per 1,000 ft^2 of gross floor area (1.39×10^8 to 3.37×10^8 J/m^2 with an average of 2.11×10^8 J/m^2).

If, in addition, school No. 18 is also omitted (to be consistent with the average fuel-oil data discussed in the next paragraph), the average value becomes 5,250 kWh per 1,000 ft^2 of gross floor area (2.03×10^8 J/m^2) for the remaining 17 schools.

Figure 2 shows, also in order of increasing amount, the yearly fuel-oil consumption in gallons/1,000 ft^2 (gross floor area). It is seen that the variations for the 19 schools were also quite high, ranging from 300 to 890 gal/1,000 ft^2 (.0122 to .0363 m^3 per m^2 of gross floor area). However, when the last two schools (Nos. 18 and 19) are omitted, the remaining 17 schools show a much narrower variation in fuel-oil consumption, ranging from 300 to 520 gal/1,000 ft^2 (.0122 to .0212 m) with an average value of 417 gal/1,000 ft^2 gross floor area (.017 m^3 per m^2 of gross floor area). The reason for the high oil consumption in school No. 19 was probably due to the use of steam for space cooling (absorption chiller), while the other schools' steam was used only for space heating and domestic hot water heating. The reason for the high oil consumption for school No. 18 is unknown, because no system data were available for this school.

Figure 3 shows the overall energy consumption pattern both at the building line and at the power generating plant for the 19 schools surveyed, in terms of Btu/ft^2 of gross floor area. The heating value of No. 6 fuel oil was assumed to be 153,000 Btu/gal (4.27×10^{10} J/m^3), and the electrical generating plant efficiency was taken to be 30 percent. It is seen that, when the last two schools (Nos. 18 and 19) are omitted, the variation of energy consumption from the lowest consumption school to the highest one for the remaining 17 schools is less than a factor of 2, with most of them lying in a fairly narrow range (60,000 to 90,000 Btu/ft^2 (6.82×10^8 to 10.23×10^8 J/m^2) at the building line).

Based on the above analysis, it is seen that for the purpose of the selection of the typical energy consumption for an existing school, the average yearly value of 5,250 kWh for electricity and 417 gallons for heating fuel oil, both on a per 1,000 ft^2 gross floor area basis (2.03×10^8 J/m^2 for electricity and .017 m^3 per m^2 of gross floor area for oil), can be used for future comparison purposes.

Table 1 Description of the 19 Schools Included in the Energy Consumption Survey

School No.	Type*	Location	Year Completed	Gross Floor Area 1,000 ft^2	Type of Wall Construction**	No. of Stories	Classroom Ceiling Heights	Ratio of Classroom Window to Exterior Wall Area	Heating System Type
1	H. S.	Brooklyn	1969	404	1	4	10'-0"	0.37	Fin-Tube Steam
2	I. S.	Brooklyn	1963	188	1	3	10'-0"	0.52	Fin-Tube Steam
3	H. S.	Bronx	1969	371	1	3	8'-9"	0.50	Fin-Tube Steam
4	H. S.	Queens	1960	246					
5	H. S.	Queens	1955	311	1	3	10'-8"	0.39	Fin-Tube Steam
6	H. S.	Queens	1965	254	1	3	9'-0"	0.58	Fin-Tube Steam
7	H. S.	Bronx	1959	288	6	4	11'-0"	0.52	Fin-Tube Steam
8	I. S.	Bronx	1970	176					
9	H. S.	Queens	1966	284	1	3	9'-0"	0.29	Fin-Tube Steam
10	I. S.	Brooklyn	1970	169	3	3	10'-0"	0.41	Fin-Tube Steam
11	H. S.	Manhattan	1958	251	5	7	11'-6"	0.25	Fin-Tube Steam
12	H. S.	Brooklyn	1958	300	1	3	8'-0"	0.56	Fin-Tube Steam
13	H. S.	Queens	1964	254	1	3	9'-3"	0.50	Fin-Tube Steam
14	I. S.	Brooklyn	1968	164	2	4	10'-4"	0.05	Fin-Tube Steam
15	I. S.	Manhattan	1958	175					
16	H. S.	Brooklyn	1969	282	4	3	11'-3"	0.49	Fin-Tube Steam
17	H. S.	Brooklyn	1964	248	1	3	8'-5"	0.42	Fin-Tube Steam
18	I. S.	Brooklyn	1966	163					
19	I. S.	Manhattan	1966	170	2	3	8'-0"	0.	Hot Water

* H. S. - High School
I. S. - Intermediate School

** Wall Type 1: 4" face brick, 2" airspace, 6" concrete block
Wall Type 2: 4" face brick, 2" airspace, 4" concrete block
Wall Type 3: 4" face brick, 6" concrete block
Wall Type 4: 10 1/2" masonry, 2" airspace, 3" plaster
Wall Type 5: 4" glass block
Wall Type 6: 10 1/2" masonry

$1\ ft^2 = 9.29 \times 10^{-2}\ m^2$
$1\ ft = 3.048 \times 10^{-1}\ m$
1 in. = 2.54 cm

Table 1 - continued

School No.	Cooling System Type	Ventilation System for Classroom	Ventilation cfm/Typical Classroom	Classroom Lighting Watt/ft^2 (Floor)	3-Year Avg. Energy Consumption/Year: Electricity kWh/1,000 ft^2 (Gross Floor)	3-Year Avg. Energy Consumption/Year: #6 Fuel Oil Gal/1,000 ft^2 (Gross Floor)
1	None	Exhaust Fan	560	2.0	3,633	408
2	None	Exhaust Fan	560	2.4	3,963	368
3	None	Exhaust Fan	560	2.3	4,307	411
4	*	*	*	*	4,312	455
5	None	Exhaust Fan	560	2.5	4,512	460
6	None	Exhaust Fan	540	2.75	4,624	428
7	None	Exhaust Fan	560	2.4	4,675	339
8	*	*	*	*	4,745	305
9	Centrifugal	Exhaust Fan	560	2.3	5,030	459
10	None	Exhaust Fan	560	*	5,286	424
11	None	Exhaust Fan	600	2.4	5,659	352
12	None	Exhaust Fan	560	*	5,692	446
13	None	Exhaust Fan	540	2.85	5,916	403
14	None	Exhaust Fan	560	2.7	6,114	335
15	*	*	*	*	6,420	587
16	None	Exhaust Fan	560	2.0	6,702	409
17	None	Exhaust Fan	560	2.4	8,201	517
18	*	*	*	*	8,722	890
19	Absorption	Fan-Coil and Unit Ventilator	550	5.5	15,142	880

* Information not available.

1 kWh/1,000 ft^2 = 38,750 J/m^2
1 Gal/1,000 ft^2 = 4.07×10^{-5} m^3 per m^2
1 cfm = 4.719×10^{-4} m^3/s
1 W/ft^2 = 10.76 W/m^2

Table 2 Three-Year Averaged Monthly Electricity Consumption in 19 Schools

School No.	Gross Floor Area 1,000 ft^2	Monthly Electricity Consumption in kWh Per 1,000 ft^2 Floor Area												Yearly Total
		1	2	3	4	5	6	7	8	9	10	11	12	
1	404	326	332	384	316	362	317	181*	189*	269*	333*	318	306	3,633
2	188	379	378	403	338	386	333	232	214	269	328	354	349	3,963
3	371	416	406	460	340	363	323	178	214	311	355	543		4,307
4	246	443	434	503	358	466	443*	37*	195*	258	320	421	434	4,312
5	311	453	420	487	380	496	386	149	101	309	447	455	429	4,512
6	254	461	444	448	517	504	375	104	110	298	426	474	463	4,624
7	288	424	458	529	440	474	385	135	117*	332*	442	457	482	4,675
8	176	432	430	476	399	477	455	236	249	317	403	434	437	4,745
9	284	487	479	555	444	539	431*	150*	155	365	466	472	487	5,030
10	169	667**/426*	389	518	440	454	372	366*	344*	266*	398	433	639**/419*	5,286/4,825
11	251	551	540	603	492	581	451	261	207	360	521	534	558	5,659
12	300	530	552	641	484	625	524	141	168	368	532	572	555	5,692
13	254	561	540	601	464	570	458	346	373	403	511	535	554	5,916
14	164	553	524	544	485	549	510	417	422	507	532	542	529	6,114
15	175	616	595	631	567	631	534	338	377	406	557	588	580	6,420
16	282	617	576	660*	540*	664	567	393	399	495	583	605	603	6,702
17	248	815	729	815	734	763	685	366	384	574	768	802	766	8,201
18	163	809	784	825	801	788	676	549	633	627	681	765	784	8,722
19	170	1,280	1,129	1,257	1,240	1,306	1,381	1,273	1,296	1,261	1,271	1,212	1,233	15,142

* 2-year average

** Extra large during the opening year operation

1 kWh/1,000 ft^2 = 38,750 J/m^2
1 ft^2 = .093 m^2

Table 3 Three-Year Averaged Monthly Fuel-Oil Consumption in 19 Schools

School No.	Gross Floor Area 1,000 ft^2	Monthly Fuel-Oil Consumption in Gallons Per 1,000 ft^2 Floor Area 1	2	3	4	5	6	7	8	9	10	11	12	Yearly Total
1	404	78.20	77.07	63.08	42.38*	12.45*	2.78*	3.33*	3.18*	2.70	10.37*	48.94	63.88	408.4
2	188	74.56	75.13	57.39	31.42*	8.48	5.25	3.56	4.44	5.32	7.52*	39.33	55.23*	367.6
3	371	78.31	79.40	66.19	30.08	13.82*	2.29*	0.81*	2.29*	2.58*	20.01*	52.27*	62.42*	410.5
4	246	91.98*	88.13	71.26	36.11	11.01*	5.49*	2.39*	2.75*	4.27*	18.68*	50.68*	71.72*	454.5
5	311	94.96	79.83	72.99	35.69	8.25	4.02*	2.25*	1.40	4.29	25.61	57.23	73.64	460.2
6	254	88.31	76.74	62.68	34.53	12.35	9.38	12.55**	1.22*	2.15	4.71	52.48	71.31	428.4
7	288	66.13	64.05	53.33	29.28	6.83	2.95	1.46	2.08	2.78	15.57	37.34	56.78	338.6
8	176	60.69	45.81	53.83	21.69	7.68	2.56	0.73	0.86	3.58	12.77	52.79	42.38	305.4
9	284	88.23	79.35	71.51	40.58	14.85	3.44	2.22	2.71	3.31	26.94	56.02	69.67	458.8
10	169	81.59	69.57	50.90	34.94	14.20*	7.10*	6.59**	4.73**	4.74*	29.33	56.20*	64.31	424.2
11	251	72.89	61.45	63.17	23.43	10.34	5.00	4.36*	1.35*	2.58*	17.36*	41.58*	47.98*	351.5
12	300	89.60	85.38	68.55	37.68	13.08*	3.17*	4.35*	1.84*	4.17*	8.33*	57.29*	72.67*	446.1
13	254	82.33	76.50	60.06	31.75	9.38	5.58	5.91**	5.43	5.21	16.67	41.54	62.39	402.8
14	164	58.95	65.85	53.61	30.69	10.09	4.83	0.71	0.46*	2.01	13.21	40.14	54.71	353.3
15	175	91.95*	95.08	89.00	41.96	28.70	23.65**	5.71	12.60	10.48	23.64	64.13	99.79	586.7
16	282	66.19	77.19	65.41	39.18*	12.76	2.73	3.09	1.07	2.06	19.91	52.98	66.17*	408.7
17	148	97.00	100.20	81.93	47.09*	11.77	4.54	5.02	4.24	4.09	18.43*	59.36	83.42	517.1
18	163	183.91	150.90	151.36	60.55*	56.41	9.50	5.43	9.69	14.93	17.88	71.43	151.78	889.8
19	170	92.80	104.34	53.11	49.02	33.32	87.82*	94.16*	95.77	67.53	47.83*	69.32*	84.98	880.0

* 2-year average

** Single year data

1 ft^2 = .093 m^2
1 Gal/1,000 ft^2 = 4.07×10^{-5} m^3 per m^2

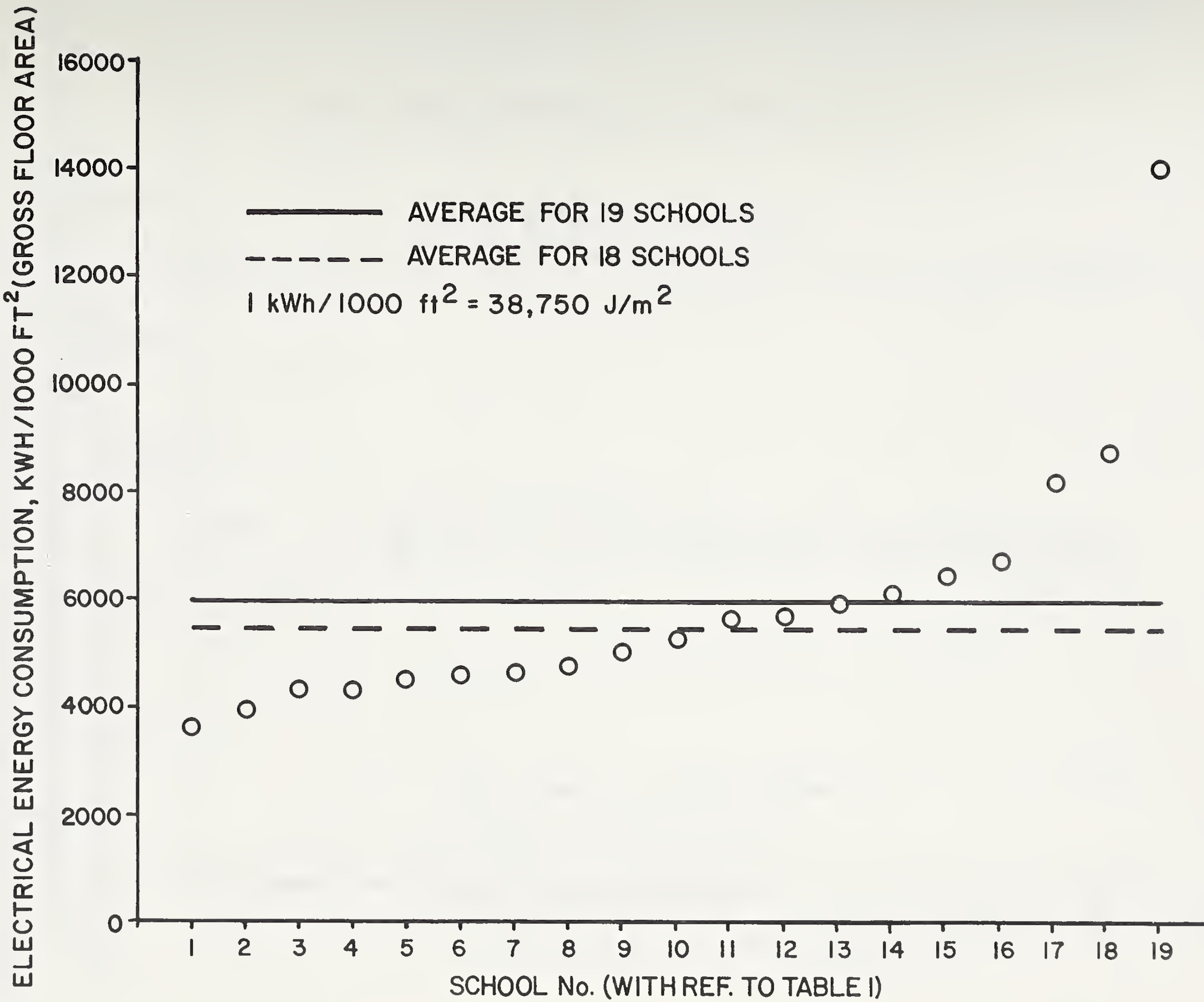


Figure 1 Averaged (3-Year) Yearly Electrical Energy Consumption in 19 Schools

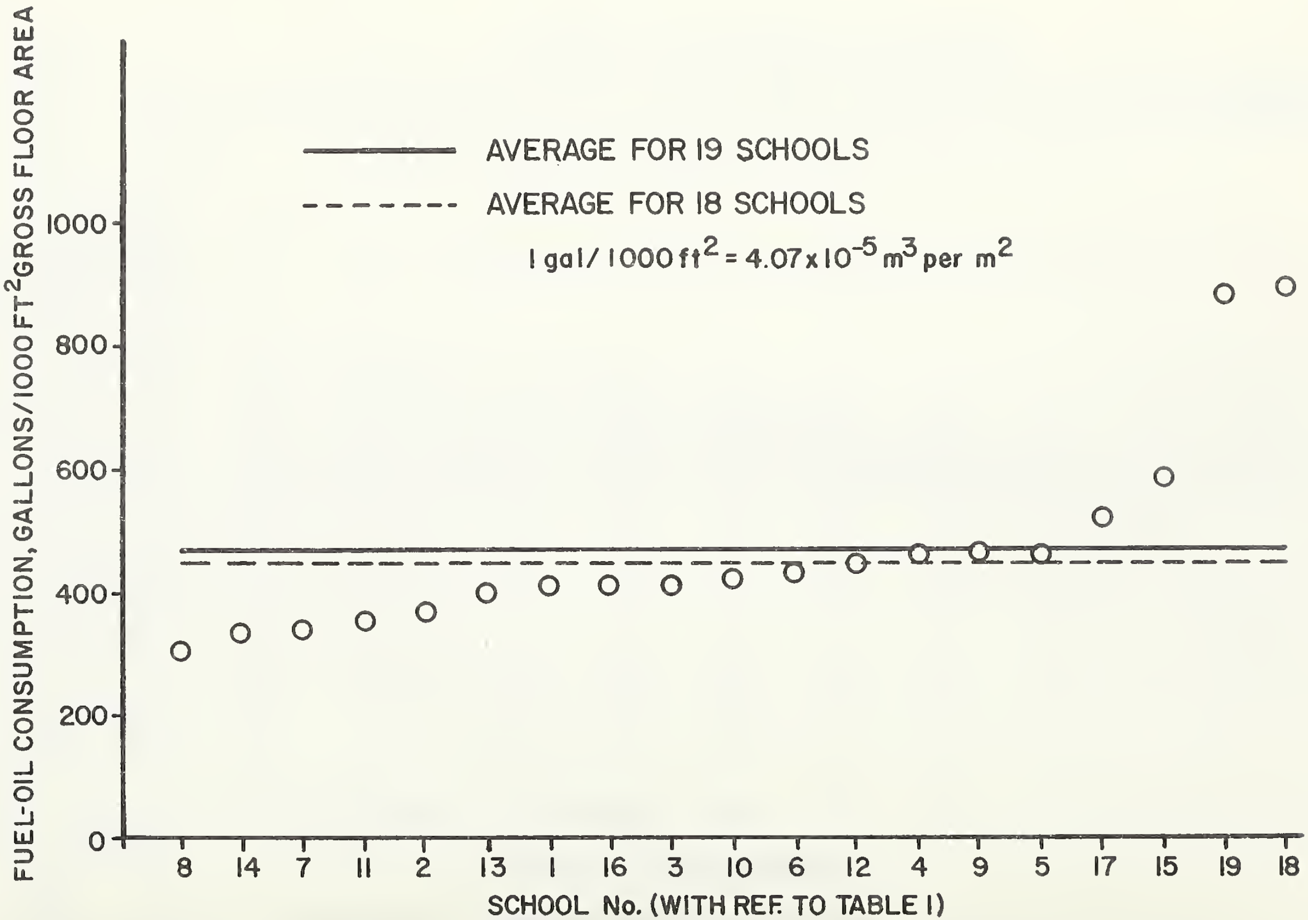


Figure 2 Averaged (3-Year) Yearly Fuel-Oil Consumption in 19 Schools

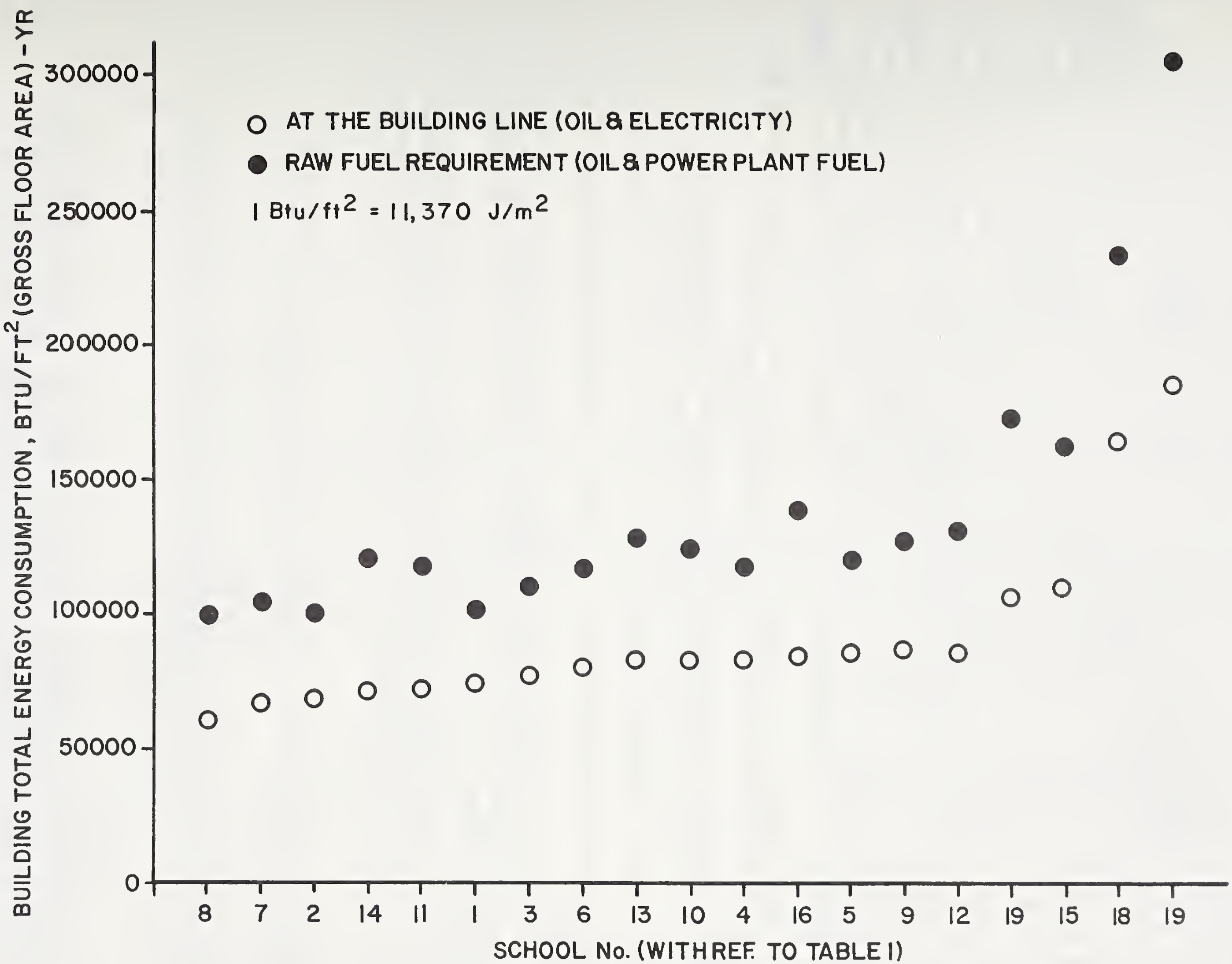


Figure 3 Averaged (3-Year) Yearly Energy Requirement in 19 Schools

2.2 Observations on the Operating Schedules of Existing Schools

The designed lighting level, ventilation rate, type of building shell construction, glass area, and number of occupants are not the only parameters that affect the energy requirements of a school building. The way a school is operated (such as the daily and weekly class schedule, the interior temperature setting, and the schedule for turning on and off the various mechanical equipment components) also has a major impact on its actual energy consumption. For example, a building with its lights on 24 hours a day will consume twice as much electrical energy as the same building with lights on only half the time. It is estimated that with every degree increase in thermostat setting above 70 °F (21.4 °C), 2.5 to 3 percent additional heating energy is required[6/] in a 5,000 degree-day climate. Therefore, for a detailed energy analysis of a school building, the various operating schedules of the school have to be determined. To this end, field trips to 5 of the 19 schools were taken jointly with the Board of Education and its principal investigator, the Richard Stein and Associates, to collect these data. The 5 schools were Nos. 2, 6, 10, 17, and 19. Two of the schools were at the high and low ends of the energy consumption profile as seen from Figure 3 (No. 2 at the low end and No. 19 at the high end), while the other 3 schools were closer to the average energy consumption. The reason for selecting the two extremes was to determine whether there was any relation between the energy consumption and the operating schedules. The results of this survey with respect to the daily class schedule, daily lighting schedule, daily heating and ventilation schedule, weekend schedules, and indoor temperature settings of classrooms, gymnasium, auditorium and cafeteria, are tabulated in Table 4. The information contained in Table 4 was obtained by observation and talking to the school custodian, engineer, and fireman.

The following summary of the operation of the 19 schools is taken partly from the data in Table 4, and supplemented by other information recorded during the visits.

1. Daily classes for the intermediate schools start at 8:30 a.m. and end at 2:50 p.m., which is also the period when the classroom lights are on.

2. Daily classes for the high schools start at 7:30 a.m. and end at 4:30 p.m.

3. School space used during nighttime is generally for adult activities and sports.

4. School space used during weekends is generally limited to Saturday use of the gymnasium. Schools are generally closed during holidays and during Christmas and Spring recess.

5. During the heating season, the boilers are fired in the morning approximately 1 1/2 to 2 hours before the students arrive to preheat the school buildings, and are shut off approximately 1/2 to 1 1/2 hours before the students are dismissed from the school.

6. During the heating season, the classroom exhaust schedule and the gymnasium, auditorium, and cafeteria ventilation schedules are identical to the boiler operating schedule.

7. The thermostat settings of the schools are in the 70 to 73 °F (21.4 to 23.1 °C) range and are locked and controlled by the fireman. However, due to the location and mounting of the thermostats, they are sometimes either blocked accidentally by a cabinet or recessed such that they will not give an accurate control of the room temperature.

8. It is possible to shut off the heat to unoccupied classrooms during nighttimes and weekends, while maintaining heat to the gymnasium. This is accomplished by closing the valve leading to the steam supply pipe serving the unoccupied classrooms. This procedure was carried out by the fireman of school No. 2, and may partly account for the low fuel-oil consumption shown in Table 1.

9. The auditorium in the schools was usually unoccupied or only sparsely occupied during the school day.

Table 4 Operation Schedules of the 5 Schools Visited

School No.	2	6	10	17	19
No. of Day Students	1,720	4,000	1,500	4,000	1,500
School Hours					
Weekdays	8:30 a.m. - 3:00 p.m.	7:00 a.m. - 5:00 p.m.	8:30 a.m. - 3:00 p.m.	7:30 a.m. - 4:30 p.m.	8:30 a.m. - 3:00 p.m.
Week Nights	6:00 p.m. - 10:00 p.m.	7:00 p.m. - 9:30 p.m.	7:00 p.m. - 10:00 p.m., 3/Week	6:00 p.m. - 10:00 p.m.	6:00 p.m. - 10:00 p.m., 3/Week
Weekends	Saturday, 9:00 a.m. - 12:00 noon	Saturday, 10:00 a.m. - 5:00 p.m.	Saturday, 9:00 a.m. - 12:00 noon	10:00 a.m. - 3:00 p.m.	10:00 a.m. - 5:00 p.m.
Space Occupied					
Weekdays	All	All	All	All	All
Week Nights	Gymnasium, Auditorium	Gymnasium, 30 Classrooms	Gymnasium, 15% Classrooms	Gymnasium, 12 Classrooms	2nd Floor (25%)
Weekends	Gymnasium, Auditorium	Gymnasium	Gymnasium	Gymnasium	Gymnasium
Lighting					
Weekdays	All	All, 20% Auditorium	All, 25% Auditorium	All	All
Week Nights	Corridor, Gymnasium, Auditorium	Corridor, Gymnasium, 30 Classrooms	Corridor, Gymnasium, 15% Classrooms	Corridors, Gymnasium, 12 Classrooms	Corridor, Cafeteria, Gymnasium, Classrooms
Weekends	Corridor, Gymnasium, Auditorium	Gymnasium	Corridor, Gymnasium	Gymnasium	Corridor, Gymnasium
Thermostat					
Classrooms	72 °F	73 °F	72 °F	72 °F	72 °F
Gymnasium	70 °F	70 °F	70 °F	70 °F	70 °F
Auditorium	70 °F	70 °F	70 °F	70 °F	70 °F
Cafeteria	70 °F	70 °F	70 °F	70 °F	70 °F
Boiler Schedule					
Heating Season	2 Boilers	2 Boilers	2 to 3 Boilers	2 to 3 Boilers	2 Boilers
Other Seasons	1 Boiler	1 Boiler	1 Boiler	1 Boiler	2 Boilers
Boiler Schedule					
Weekdays	7:00 a.m. - 2:30 p.m.	6:00 a.m. - 3:00 p.m.	7:00 a.m. - 2:30 p.m.	5:00 a.m. - 6:00 p.m.	7:00 a.m. - 3:00 p.m.
Week Nights	6:00 p.m. - 8:00 p.m.	7:00 p.m. - 9:00 p.m.	6:00 p.m. - 9:00 p.m.	6:00 p.m. - 9:00 p.m.	6:00 p.m. - 9:00 p.m.
Weekends	Saturday, 8:00 a.m. - 10:00 a.m.	Saturday, 9:00 a.m. - 2:00 p.m.	Saturday, 7:00 a.m. - 10:00 a.m.	9:00 a.m. - 2:00 p.m.	11:00 a.m. - 5:00 p.m.

Table 4 - continued

School No.	2	6	10	17	19
Ventilation					
Weekdays	All (7:00 a.m. - 2:30 p.m.)	All (6:00 a.m. - 3:00 p.m.)	All (7:00 a.m. - 2:30 p.m.)	All (6:00 a.m. - 4:30 p.m.)	All (7:30 a.m. - 3:00 p.m.)
Week Nights	Recirculate	Gymnasium (7:00 p.m. - 9:00 p.m.)	Gymnasium (7:00 p.m. - 10:00 p.m.)	Gymnasium, 12 Classrooms (6:00 p.m. - 9:00 p.m.)	2nd Floor (6:00 p.m. - 9:00 p.m.)
Weekends	Recirculate	Gymnasium (9:00 a.m. - 2:00 p.m.)	Gymnasium (7:00 a.m. - 10:00 a.m.)	Gymnasium (9:00 a.m. - 2:00 p.m.)	2nd Floor (11:00 a.m. - 5:00 p.m.)
Space Heated					
Weekdays	All	All	All	All	All
Week Nights	Gymnasium, Auditorium	Classrooms, Gymnasium	Classrooms, Gymnasium	Gymnasium, Classrooms	Gymnasium, 25% Classrooms
Weekends	Gymnasium, Auditorium	Classrooms, Gymnasium	Classrooms, Gymnasium	Gymnasium, Classrooms	Gymnasium

°C = 5/9 (°F - 32)

10. School No. 19 was the only school visited that had air-conditioning. The school was a windowless school with a higher than usual lighting level (5.5 watt/ft^2 (59.2 W/m^2) classroom floor area) and a longer than usual school schedule (open 7 days/week, 52 weeks/year for both teaching and community activities). The boilers supplied steam for space heating during the winter and for the absorption chillers during cooling season. The windowless design and the operating schedule probably caused the high energy consumption rate for this school.

The information gathered during the visit to the schools was used as input to the NBS-developed building thermal load determination program in order to obtain a detailed energy consumption pattern of a typical existing school. The computer analysis is described in the following section.

3. Computerized Analysis of the Energy Consumption Pattern of a Typical Existing School

3.1 Calculation of Indoor Space Conditions by Building Thermal Simulation

Numerous papers have been published and calculation manuals prepared on the subject of heating/cooling load determination. Very few of the computerized models, however, have the capability of handling fluctuations in indoor air temperature as in the case of the schools studied in this report where the boilers are actually shut down during nonoccupied periods of time and the indoor temperature is allowed to drift below the set value of the thermostat.

The heat transfer calculations for room temperature prediction are similar to the heating/cooling load calculations. The former, however, are somewhat more complex than the latter because they require exact heat transfer calculations for heat conduction through exterior surface and infiltration heat exchange. The National Bureau of Standards, over the last several years, has developed a computer program which computes the room heating/cooling load requirement, as well as the temperature fluctuation of a room not heated or air-conditioned, when the building is subjected to hour-by-hour randomly fluctuating outdoor climatic conditions. The program is called "NBSLD" and consists of various subroutines for calculating heat gains and losses, which are similar to those recommended by the ASHRAE Task Group on Energy Requirements[7/]. One major extension of the program beyond the recommended ASHRAE Task Group algorithms is a routine called RMTPK, which solves for the hour-by-hour heating/cooling load requirements or temperature variations, taking into account the transient heat conduction and thermal storage in the building and internal mass, through the use of a series of simultaneous heat balance equations. The details of this routine, and the general description of the overall program, are given in references [5] and [8].

3.2 Construction Data and Operation Schedules of the Selected School

In order to aid in the design of new energy conserving schools and to investigate the application of the NBS computer program NBSLD to school design, one of the schools visited during the field trip was selected for a detailed analysis of its energy consumption pattern with respect to its requirements in heating, ventilation, lighting, and mechanical equipment operation. Once a suitable mode for the energy consumption in an existing typical school is established, areas of major energy consumption can be identified, and new designs can be devised and applied to minimize or reduce the energy requirements in these major areas.

The school selected for this detailed study was school No. 6 because its yearly consumption in fuel oil was approximately the average of the 19 schools studied. Since the computer program "NBSLD" is a thermal energy analysis program and the space heating requirement of a building is intimately associated with the building shell design and ventilation requirement, emphasis was placed on selecting a school which has an average fuel-oil consumption.

The No. 6 school selected for the analysis is a high school facility having an overall floor area of 254,000 sq. ft. (23,600 m^2) and is located in Queens, New York. The facility is composed of 3 buildings: a 3-story classroom and administration building, a gymnasium,

and a cafeteria and auditorium building with a basement which houses the shops and special purpose classrooms. A schematic of the three buildings is shown in Figure 4. The major features of the 3 buildings are described in Table 5, and the operating schedules for the lighting, ventilation, and occupancy during weekdays are given in Figures 5 through 7.

During Saturday, only the gymnasium is open (from 10:00 to 17:00 on a 24-hour clock) with 50 percent of the lights turned on, and 100 percent ventilation (from 9:00 to 13:00). The classroom building is heated from 9:00 to 13:00 due to its fin-tube radiator configuration where the flow of the steam into the radiator is controlled only by the room thermostat. The exhaust fans, however, are assumed to be off. The cafeteria and auditorium buildings are not heated. The whole school is considered closed during Sunday and holidays including the whole spring and winter recess periods.

During the occupied period, the buildings are assumed to be ventilated with fresh air according to the rates and schedules shown in Table 5 and Figure 7. When the ventilation systems are off, an air infiltration rate of 1/4 air change per hour is assumed for all buildings. The value 1/4 is based on an actual measurement undertaken at school No. 10 which has a similar type window construction as school No. 6. Details of that test will be discussed later in this report.

In order to compute the hour-by-hour heating loads or temperature variations, actual weather data typical of the New York City location were required on an hourly basis for one year. The school year September 1962 to June 1963 was selected from the ten-year period of 1955-1964. The months included in the selected period contained neither the coldest nor the warmest month during the major heating season of December to February when compared with the corresponding months over the ten-year period.

A comparison of the average monthly temperatures for the selected weather year with the three-year period of 1970-1973, where actual fuel-oil data are available, is shown in Figure 8.

3.3 Analysis and Discussion of Results

The results of the computer simulation are shown in Figures 9 through 12 and in Tables 6 and 7. The computations were done for ten months only, since the school had no cooling equipment and the summer schedules for the school were not available. The calendar for the school year 1973-74 was used to determine the dates of holidays and major recesses, because the selected weather year had the same calendar as the 1973-74 period.

Figure 9 shows the result of the computed monthly fuel-oil consumption in gallons per 1,000 ft^2 gross floor area and the 3-year averaged measured fuel-oil consumption, and Figure 11 shows the same result as compared with the measured monthly consumption of the 3-year data year by year. An average heating value of 153,000 Btu/gal (4.27×10^{10} J/m^3) of No. 6 oil, and a seasonal boiler efficiency of 65 percent were assumed in converting the heating load to gallons of oil. An average of 3 gallons/1,000 ft^2 (12.2×10^{-5} m^3 per m^2 of gross floor area) for domestic hot water heating was added to the computed space heating consumption. This particular value was chosen by examining the school oil consumption for the months of May, June, and September where the only requirement for the fuel oil was for domestic hot water heating. It is seen that the computed results and the school usage data show fairly good agreement for both the numerical value and the trend of monthly usage. The agreement between computed and observed fuel requirement in Figure 9 indicates that the computer model was a good representation of the energy use processes for this school.

Figures 10 and 12 show the same type of comparison for the electrical energy usage for the 10-month period. It is seen that the months of January, March, May, June, September, and October compare fairly well with the actual consumption while the remaining 4 months deviate significantly from the measured data. It should be noted, however, that those months that show a substantial deviation all had a number of holidays or major recesses. The schedules for lighting and equipment operation assumed that the entire school was closed during those periods, while in actual practice the school may have been opened for either school officials or for some special purpose such as a major sport event or a stage play or for community use. This can be seen by examining the actual usage data (e.g., the months of December and January

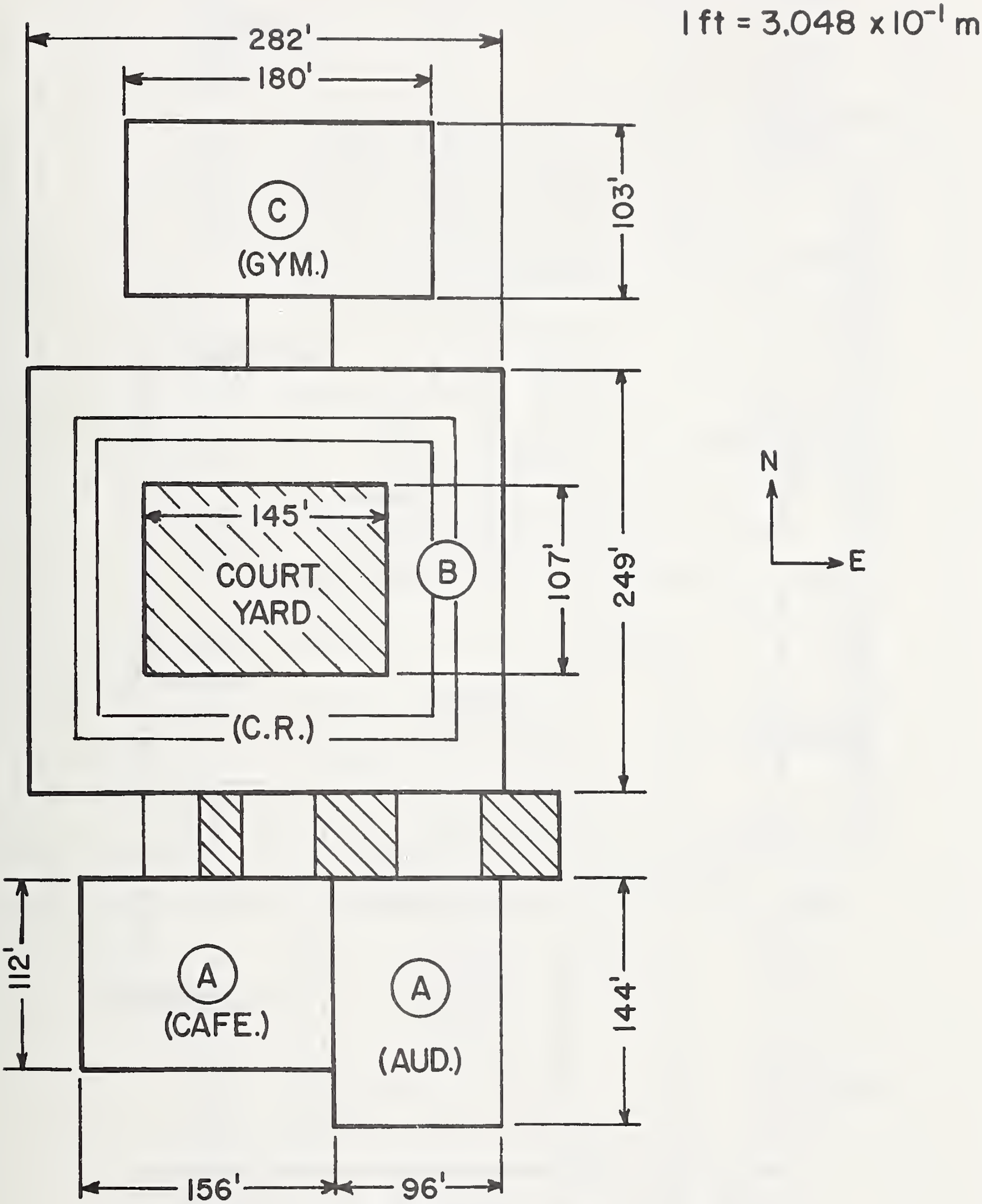


Figure 4 Schematic of School No. 6

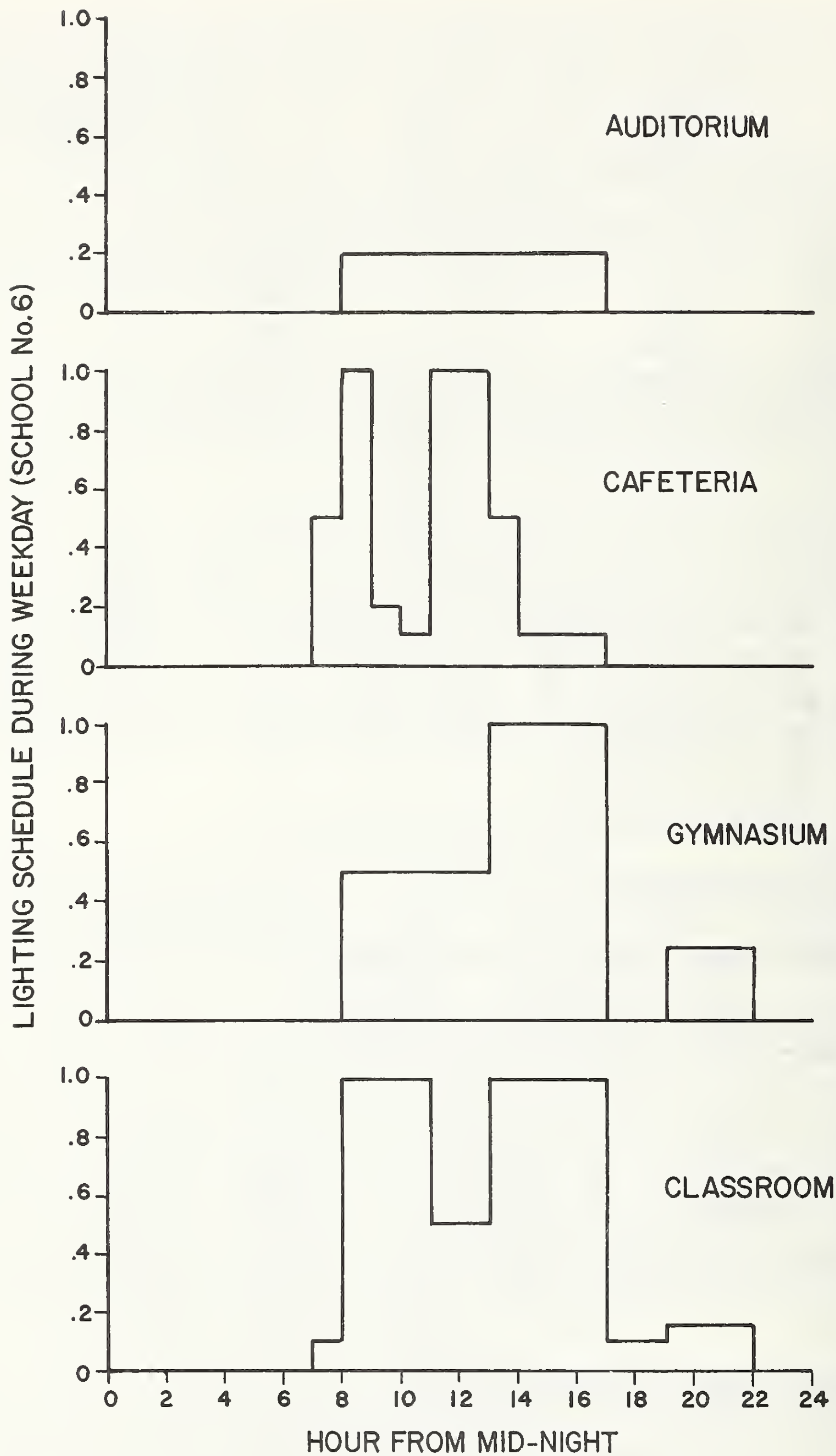


Figure 5 Lighting Schedules of School No. 6 During a School Day (Heating Season)

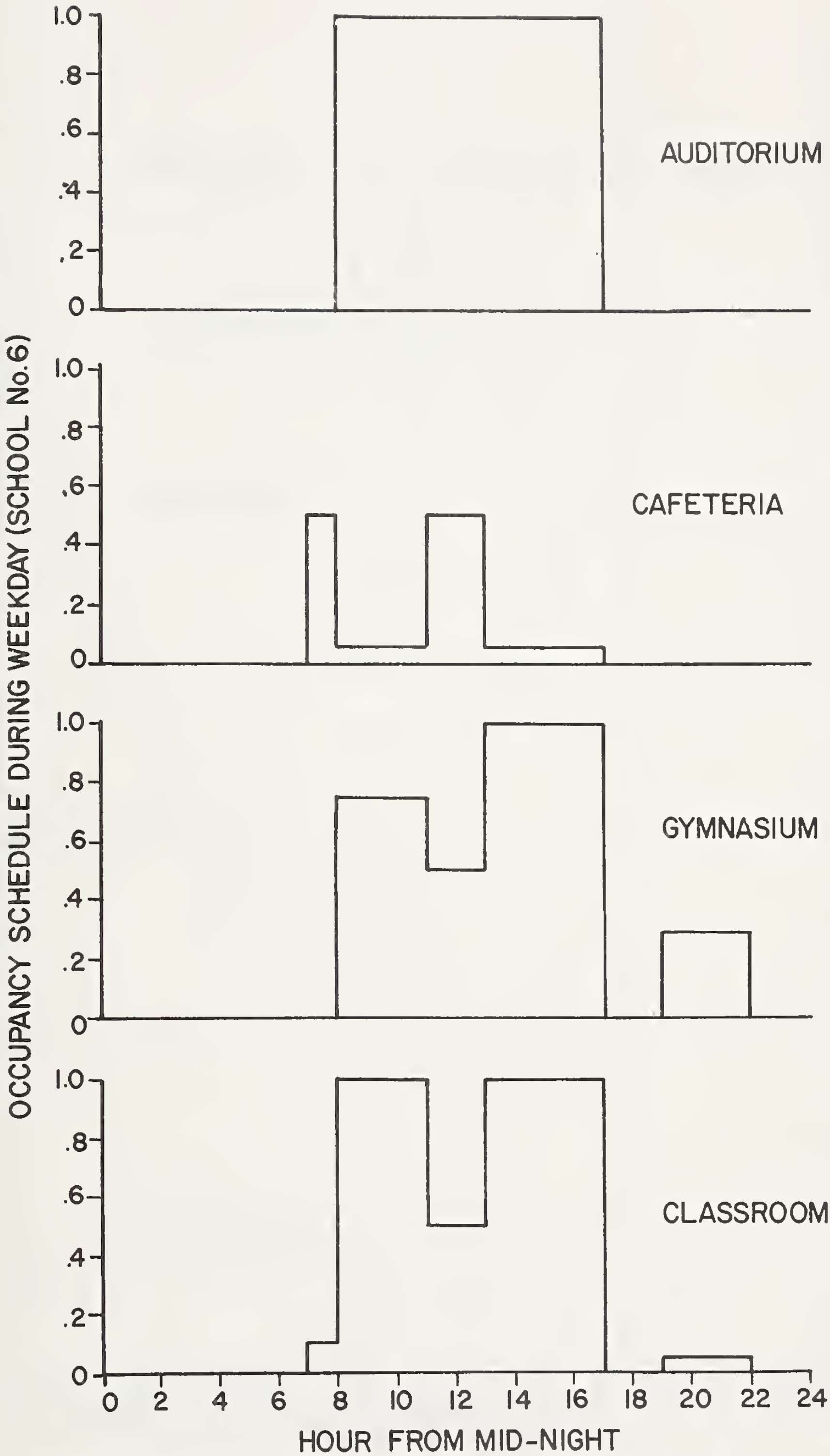


Figure 6 Occupancy Schedules of School No. 6 During a School Day (Heating Season)

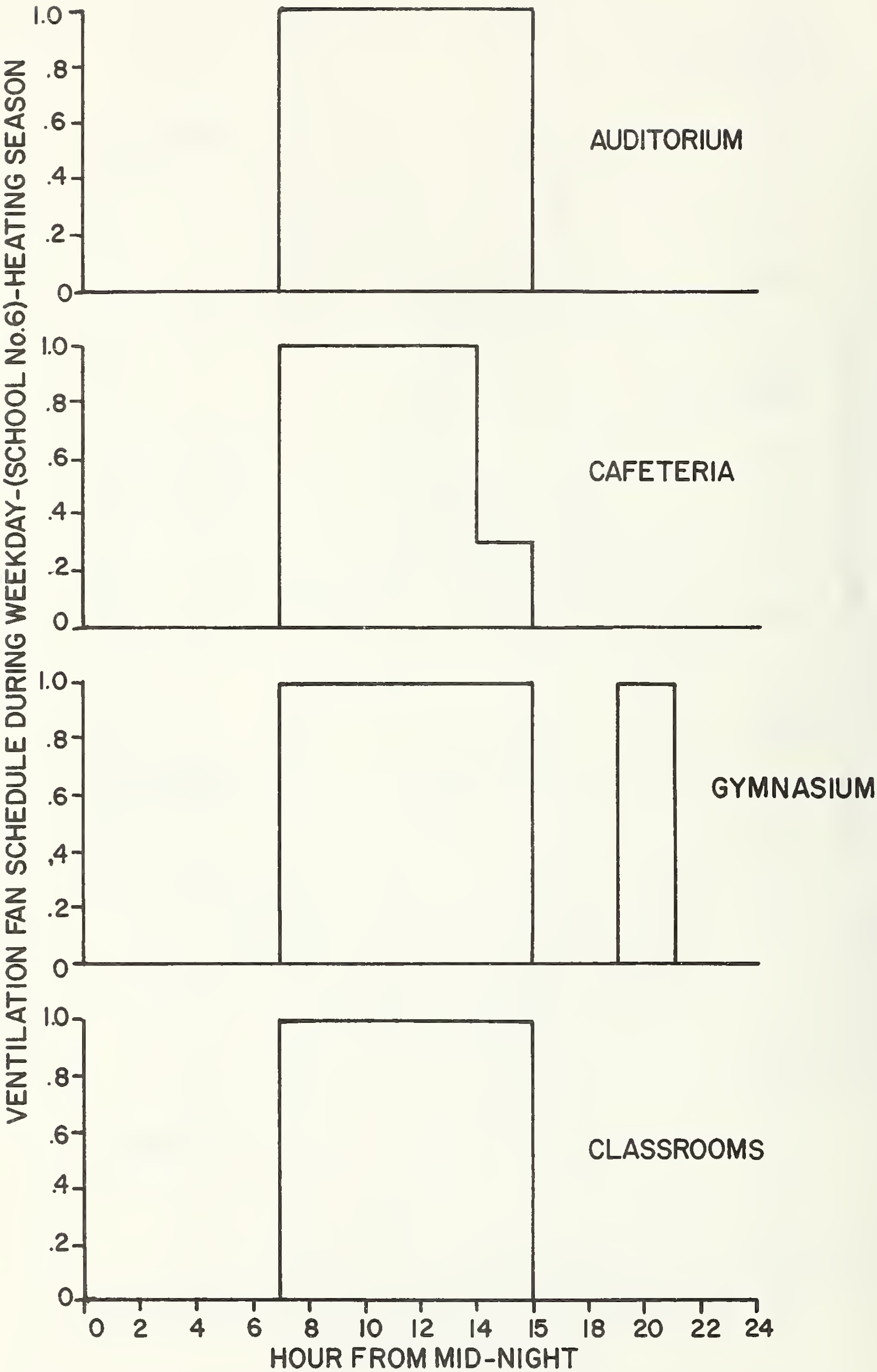


Figure 7 Ventilation Fan Schedules of School No. 6 During a School Day (Heating Season)

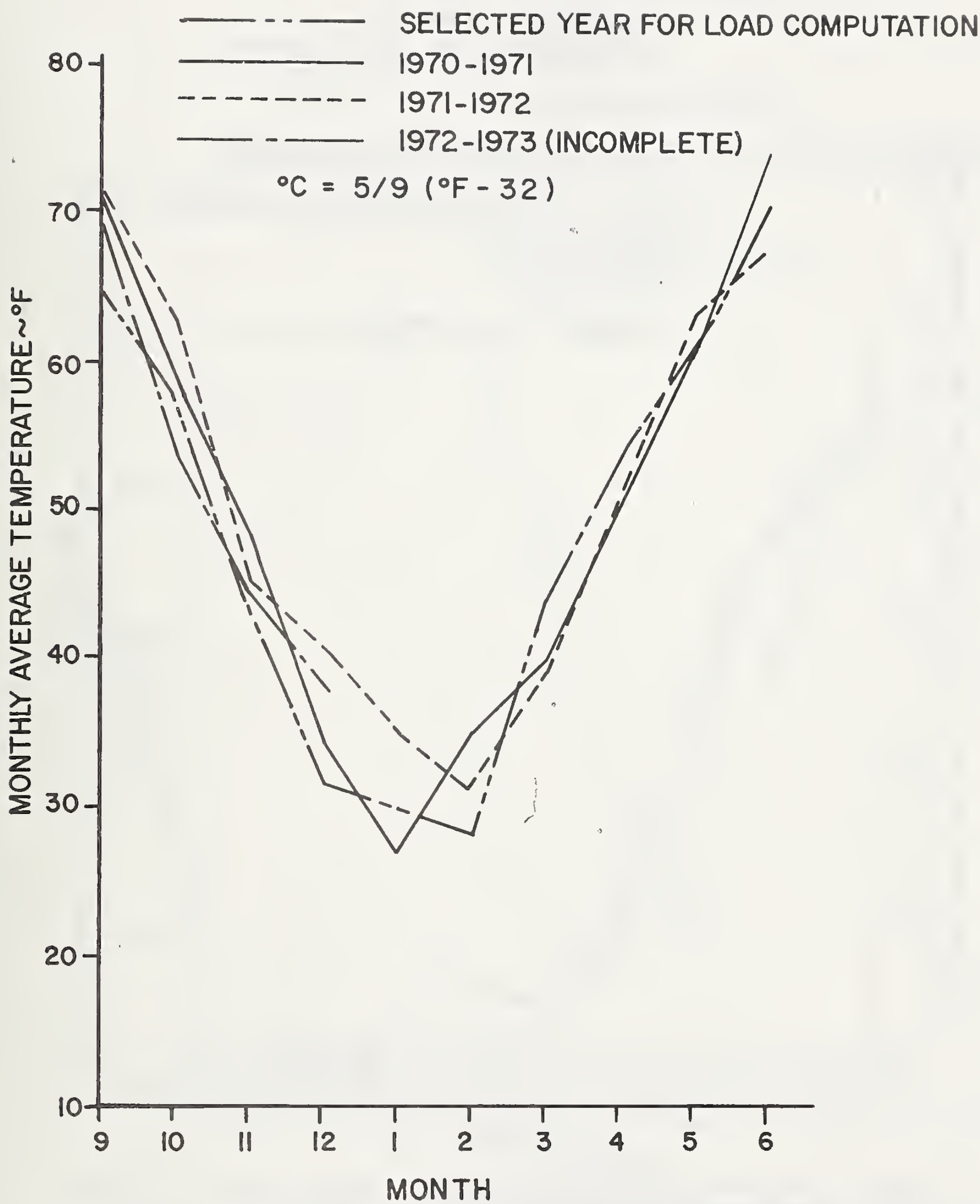


Figure 8 Comparison of the Monthly Average Temperatures for the Selected Weather Year and the Years 1970-1973

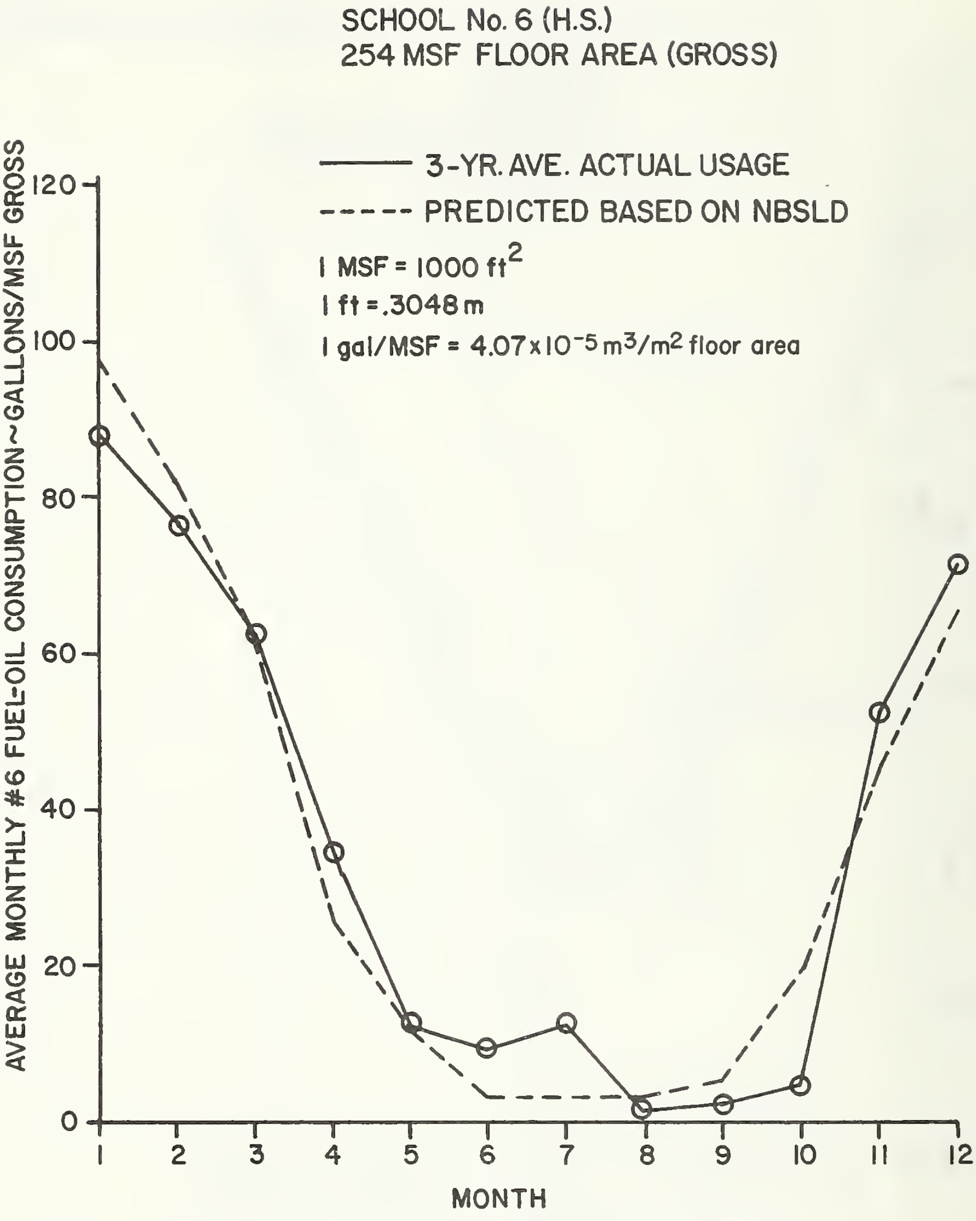


Figure 9 Comparison of Predicted and Actual Measured Monthly Fuel-Oil Consumption in School No. 6

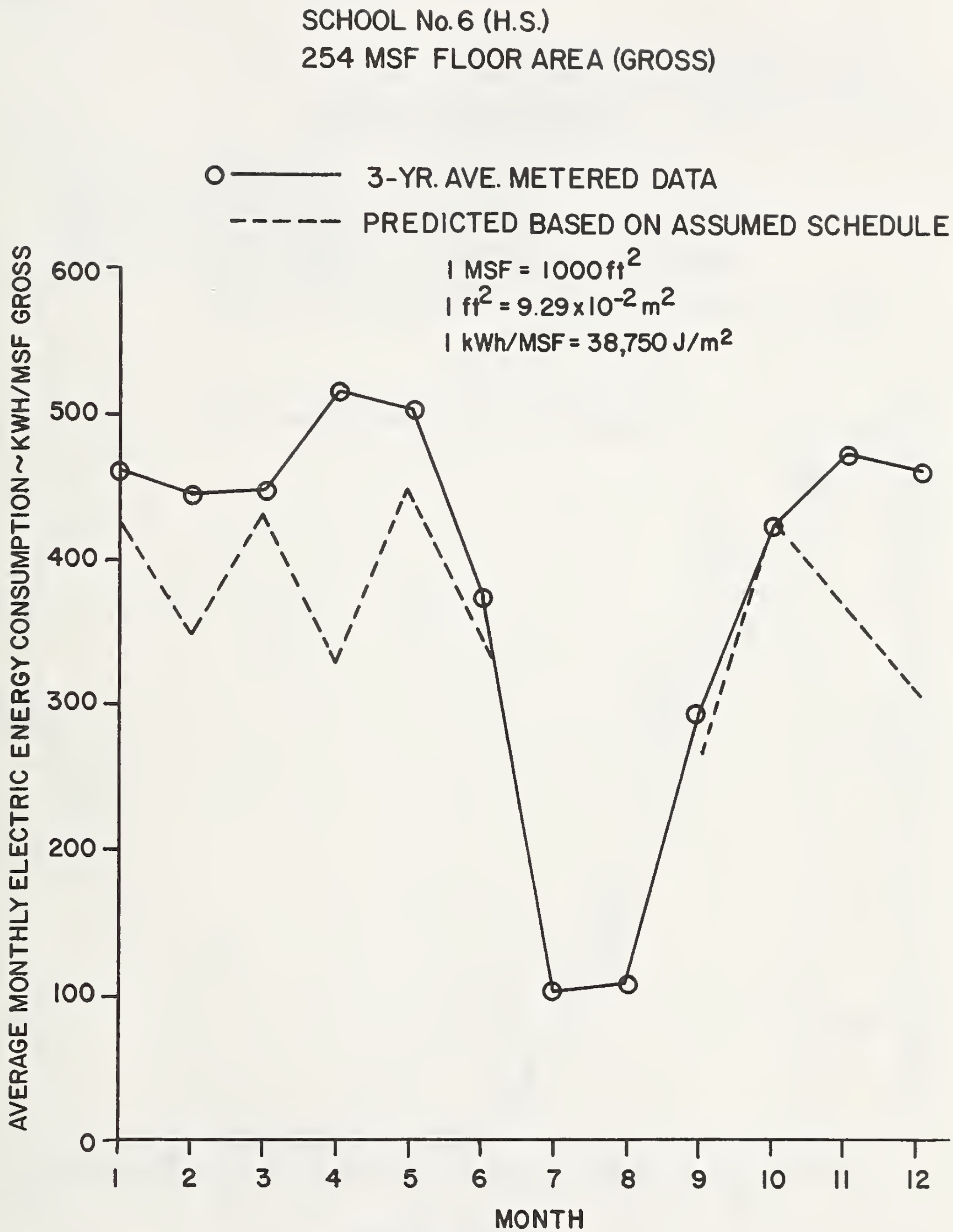


Figure 10 Comparison of Predicted and Actual Measured Monthly Electrical Energy Consumption in School No. 6

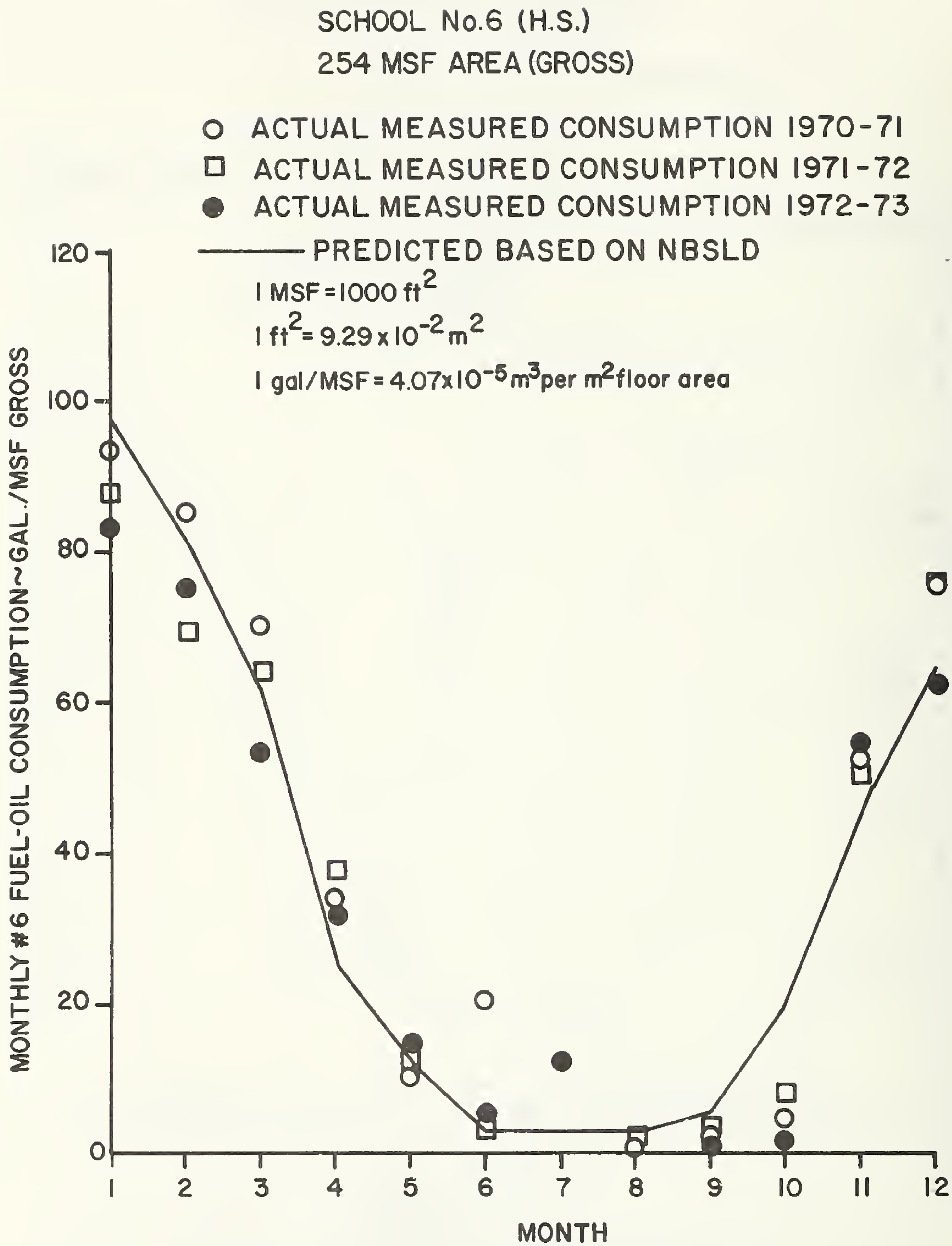


Figure 11 Comparison of Actual Measured Monthly Fuel-Oil Consumption With Corresponding Predicted Values

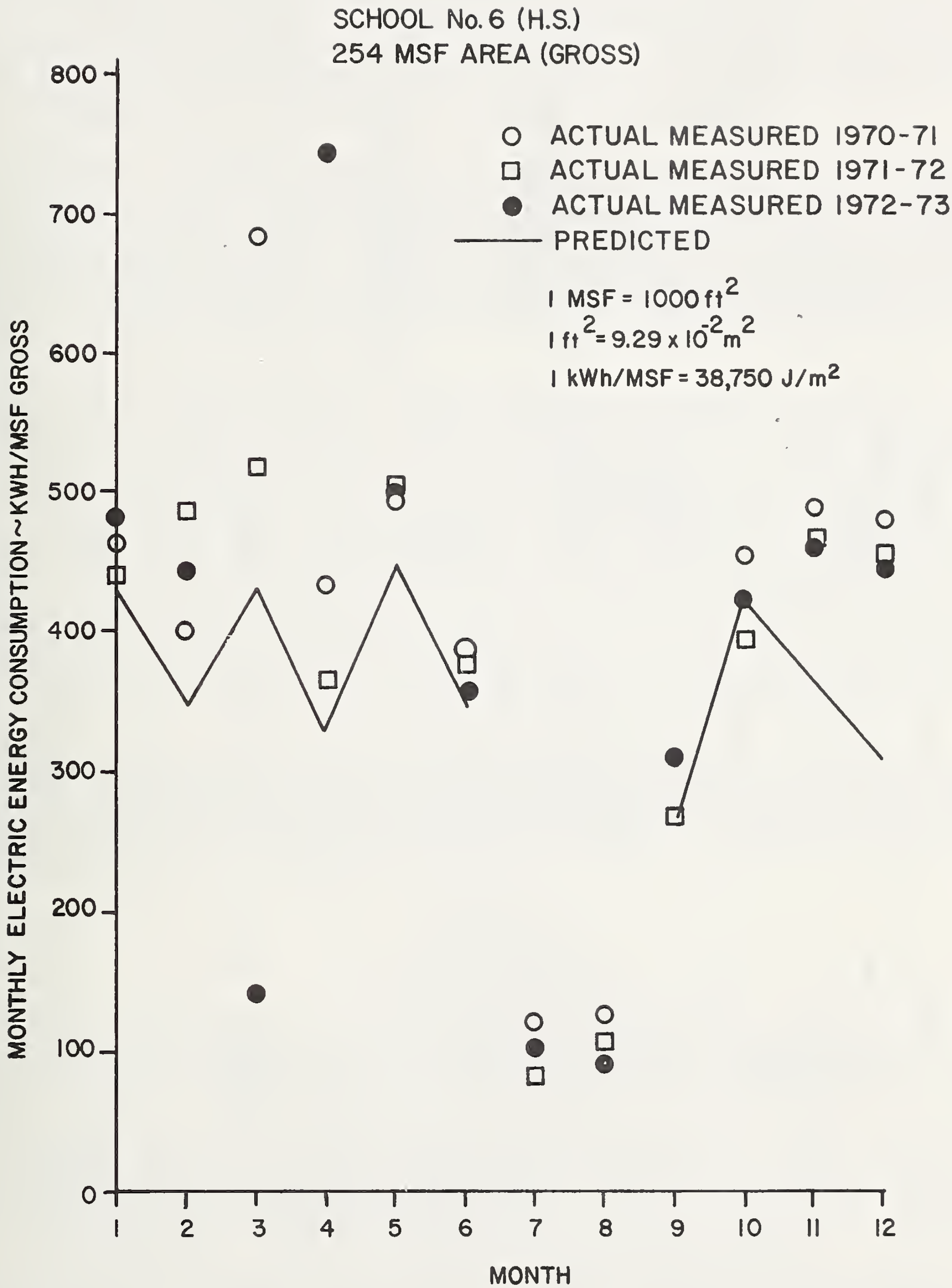


Figure 12 Comparison of Actual Measured Monthly Electrical Energy Consumption With Corresponding Predicted Values

Table 5 Major Data on Buildings in School No. 6 for Computerized Energy Analysis

Building No.	A-Auditorium	A-Cafeteria	B-Classroom	C-Gymnasium
Building Type	1-Story W/Basement	1-Story W/Basement	3-Stories, Double Load Corridors	1-Story
Overall Dimensions, ft	96 x 144 x 45	156 x 112 x 29	282 x 249 x 36	180 x 103 x 36
Ceiling Height	30'-8" 11'-0" - Basement	16'-0" 11'-0" - Basement	9'-3"	31'-0"
Wall Construction	4" Face Brick 2" Airspace 6" Concrete Block 3/4" Plaster	4" Face Brick 2" Airspace 6" Concrete Block 3/4" Plaster	4" Face Brick 2" Airspace 6" Concrete Block 3/4" Plaster	4" Face Brick 2" Airspace 8" Concrete Block 3/4" Plaster
Roof Construction	1/2" Built-up Roof 5" Insulated Concrete 8" Heavyweight Concrete	1/2" Built-up Roof 5" Insulated Concrete 8" Heavyweight Concrete	1/2" Built-up Roof 5" Insulated Concrete 8" Heavyweight Concrete	1/2" Built-up Roof 3 1/2" Insulated Concrete on Steel Channel
Ground Floor Construction	6" Heavyweight Concrete	6" Heavyweight Concrete	6" Concrete Over Crawl Space	3/4" Wood Floor 2" Wood Sub-Floor 6" Concrete Over Crawl Space
Ratio, Window/Exterior Wall	0.053	0.30	0.33	0.06
Ventilation	Forced Air Supply and Return	Forced Air Supply	Open Window, Roof Top Exhaust Fans	Forced Air Supply and Return
Ventilation Rate, cfm	36,000 + 4,000	48,000	75,600 (560/Classroom)	51,000 + 6,000
Lighting Level (Maximum)	1.75 w/ft^2	5.00 w/ft^2	2.37 w/ft^2	3.55 w/ft^2
No. of Occupants (Maximum)	100	2,000	3,600	75
Infiltration, Air Change/ Hr.*	1/4 (When Unoccupied)	1/4 (When Unoccupied)	1/4 (When Unoccupied)	1/4 (When Unoccupied)

* Value based on actual measured data in school No. 10.

1 in. = 2.54 cm
1 ft = 3.048×10^{-1} m
1 $ft^3/min = 4.719 \times 10^{-4}$ m^3/s
1 w/ft^2 = 10.76 W/m^2

which had the same electricity consumption). With the school officially closed from December 24 to January 1 for the Christmas recess, the December consumption should be much lower than for January if the school was in fact closed entirely during the recess. Also, the schedule for lighting used in the computation was, at best, an estimate of the actual usage pattern which was subjected to much greater variations than space heating or ventilation equipment operations, since those operation schedules were controlled by a single person, the custodian, while the lighting switches were accessible to a large number of people.

Table 6 gives a breakdown of monthly energy usage for ventilation, heat loss through glass, heat loss due to air infiltration and conduction through the building shell, lighting, ventilation fans, and other miscellaneous equipment. Table 7 gives the various types of energy usage in terms of fraction of total energy consumption. It is seen from the two tables that during the heating season (November - February), 76 percent of the heating energy was used to heat ventilation fresh air. The fraction of energy for classroom ventilation was the largest (27 percent), followed by gymnasium (26 percent), auditorium (14 percent), and cafeteria (8.5 percent). These data showed that a significant reduction of heating energy could be obtained by reducing the rate of fresh air intake.

Table 7 shows that the fraction of heating energy used to compensate for heat loss due to fenestration was 2.5 to 2.9 percent, and for heat loss through the solid parts of the building shell and infiltration, was 17 to 19 percent, with a combined total of about 21 percent. However, this relatively small fraction does not mean that there is no need to improve the design of the building shell. The large quantity of heating energy used to heat up the outdoor fresh air for ventilation purpose overshadows the building skin loss. If the fresh air intake is reduced significantly--for example, by a factor of 2--the percent building skin loss will become larger. The heat loss through window glass was the difference between the heat loss by conduction and heat gain due to solar radiation. This loss represents only 2.5 to 2.9 percent of the total building energy usage and 10 to 14 percent of the total heat loss through building shell and by infiltration. This is because even though the amount of glass in the classroom building is large (33 percent, see Table 5), the amounts of glass in the other two buildings are small and the overall ratio of glass to exposed surfaces, including roof and ground floor, amounts to only 7 percent of the total building shell area.

Tables 6 and 7 also give the monthly electrical energy consumption for lighting and equipment operation. It is seen that lighting constituted about 80 percent of the total electrical energy usage and ventilation fans most of the remaining usage. Therefore, any significant reduction in lighting would reduce the overall electricity usage by a large amount. The power requirement for ventilation fans will be reduced if the ventilation rate for classrooms and the air supply rate to the other spaces are reduced.

4. Ventilation Test

4.1 Objective of the Test

As described in the previous section, fresh air ventilation comprises the major heating energy consumption for the existing schools. Any reduction in the ventilation rate will therefore contribute significantly to the effort in reducing fuel-oil consumption.

The purposes in providing ventilation air for a classroom are (1) to prevent the buildup of carbon dioxide gas, and to a lesser extent to prevent the reduction in oxygen supply, to levels considered harmful to the general health of the students; (2) to dilute the intensity of body odors which may be disagreeable and distracting, in a densely occupied space; and (3) to provide air movement in the classroom for the purposes of minimizing the temperature gradient and local pockets of high carbon dioxide or odor concentration.

Chapter 4 of the 1974 Applications Volume of the ASHRAE Guide and Data Book[9] states that, with regard to health consideration, 1 cfm (0.47×10^{-3} m^3/s) of outdoor air per student is required to provide the necessary oxygen content, and 4 cfm (1.89×10^{-3} m^3/s) of outdoor air per student is required to limit the CO_2 concentration to 0.6 percent by volume. These values are applicable to a room with from 110 to 457 ft^3 (3.12 to 12.98 m^3) of airspace per student. In the same reference, the requirement for odor-free air (not necessarily outdoor air) varies from 29 cfm (13.6×10^{-3} m^3/s) per student at 100 ft^3 (2.84 m^3) of airspace per student to

Table 6 Components of Total Calculated Energy Consumption by Type of Usage for School No. 6

New York City Typical Energy Usage School

Month	Space[1] Load (MBTU)	Vent. Cl.Rm. (MBTU)	Vent. Gym. (MBTU)	Vent. Cafe. (MBTU)	Vent. Audit. (MBTU)	Vent. Total (MBTU)	Glass[2] Loss (MBTU)	Total Heat Loss (MBTU)	Light. Load (kWh)	Equip. Load (kWh)	Vent. Fan (kWh)	Total Elec. (kWh)	Fuel Oil (Gal)	Total Energy Consumption (10^3 Btu)
9	11,462	18,170	24,722	0	15,381	58,272	1,476	145,515	53,621	442	12,957	67,020	1,463	452,608
10	70,965	111,365	135,141	16,338	86,288	349,133	10,601	495,878	86,720	714	20,999	108,433	4,986	1,132,971
11	193,835	314,479	299,665	66,388	188,392	868,925	33,470	1,138,541	74,275	612	17,961	92,848	11,448	2,068,492
12	330,712	444,434	438,609	113,923	232,014	1,228,981	45,595	1,635,473	62,093	510	15,101	77,704	16,445	2,781,317
1	517,464	680,830	641,596	209,085	349,021	1,880,533	58,824	2,473,778	86,720	714	20,999	108,433	24,875	4,175,893
2	427,529	558,516	543,139	164,530	285,760	1,551,946	45,064	2,055,256	70,302	578	17,067	87,947	20,666	3,462,095
3	299,506	423,918	416,096	92,401	239,401	1,171,815	31,229	1,547,101	86,851	714	21,088	108,653	15,557	2,750,990
4	104,467	150,824	151,090	40,440	114,747	457,102	10,372	637,350	66,066	544	15,995	82,605	6,409	1,262,469
5	39,167	60,472	77,293	6,159	53,181	197,105	3,861	312,053	90,824	748	21,982	113,554	3,138	867,642
6	1,761	6,297	7,177	0	1,043	14,517	46	92,059	70,302	578	17,067	87,947	926	441,792

Note: 1. Space Load denotes the load due to conduction and infiltration loss only, and excluding ventilation load.

2. Glass Loss = conduction loss through glass - solar heat gain.

3. Domestic hot water load is assumed constant and equal to 76,000 MBTU/Month and is not shown in the above table.

4. Domestic hot water load included in Total Heat Loss, Fuel Oil, and Total Energy Consumption columns.

5. Boiler seasonal efficiency assumed equal 0.65.

1 MBTU = 10^3 Btu

1 Btu = 1.056×10^3 J

1 kWh = 3.6×10^6 J

1 Gal = 3.785×10^{-3} m^3

Table 7 Types of Energy Usage as Fractions of Total Calculated Energy Consumption in School No. 6

	Month									
	9	10	11	12	1	2	3	4	5	6
(1) Ventilation Energy Usage (Heating)										
Classroom Ventilation/Total Heating	.125	.225	.276	.272	.275	.272	.274	.237	.194	.068
Gymnasium Ventilation/Total Heating	.170	.273	.263	.268	.259	.264	.269	.237	.248	.078
Cafeteria Ventilation/Total Heating	.000	.033	.058	.070	.085	.080	.060	.063	.020	.000
Auditorium Ventilation/Total Heating	.105	.173	.166	.142	.141	.139	.155	.180	.170	.012
(2) Components of Heating Energy Usage										
Total Ventilation/Total Heating	.400	.704	.763	.752	.760	.755	.758	.717	.632	.158
Glass Loss/Total Heating	.010	.021	.029	.028	.024	.022	.020	.016	.012	.000
Walls, Infiltration Loss/Total Heating	.069	.122	.141	.174	.185	.186	.173	.148	.113	.019
Hot Water/Total Heating	.521	.153	.067	.046	.031	.037	.049	.119	.243	.823
(3) Components of Electrical Energy Usage										
Lighting/Total Electrical	.800	.800	.800	.799	.800	.799	.799	.800	.800	.799
Fans/Total Electrical	.193	.194	.193	.194	.194	.194	.194	.194	.194	.194
Miscellaneous Equipment/Total Electrical	.007	.007	.007	.007	.007	.007	.007	.007	.007	.007
(4) Components of Heat Loss										
Glass Loss/Total Loss	.129	.149	.173	.138	.114	.105	.104	.099	.099	.026
Walls, Infiltration Loss/Total Loss	.871	.851	.827	.862	.886	.895	.896	.901	.901	.974

12 cfm (5.64×10^{-3} m^3/s) per student at 475 ft^3 (13.49 m^3) of airspace per student. The Occupational Safety and Health Administration (OSHA) of the Department of Labor set the limit in CO_2 concentration for an occupied space at 0.5 percent by volume. Volume 3 of the Shelter Design and Analysis[10], published by the Office of Civil Defense, Department of Defense, recommends a minimum limit of 17 percent oxygen concentration by volume and a maximum limit of 0.5 percent CO_2 concentration by volume for prolonged shelter occupancy.

In order to determine the effect of reduced ventilation rate in an existing school classroom located in an urban area, a ventilation test was conducted in the classroom of one of the 19 schools described previously in this report. The major purpose of the test was to investigate the level of CO_2 and O_2 concentration prevailing in a classroom under normal educational conditions when the ventilation rate was reduced from the designed rate. The effects on room temperature and relative humidity were also investigated, and the reactions of the students and teacher were observed to see whether there were any signs of discomfort.

The school used for this test was school No. 10 listed in Table 1. The arrangement for NBS to conduct this test was made by R. G. Stein and Associates, with the permission and cooperation of the New York City Board of Education. The period of test was 4 days in April of 1974.

4.2 Description of Test Classroom and School Schedules

The classroom selected for the test was a science classroom used as an instruction classroom for 7th and 8th graders and was located on the second floor of school No. 10 in Brooklyn, New York. The school was a single building intermediate school with about 1,500 students ranging from the 1st to 8th grade. The overall dimensions of the classroom measured approximately 25 feet wide (7.62 m) and 36 feet long (10.97 m) with a ceiling height of 10 feet (3.05 m). The room was located on the north side of the building with the north wall facing a city street. The two window sections of the north wall measured approximately 10 feet (3.05 m) by 5 feet (1.524 m) each, and were of the pull-open type with hinges located at the bottom. The windows were kept closed throughout the 4-day test period. The door in the south side of the room led into the double-loaded corridor, and the door at the west side of the room near the north windows led into a small teacher's preparation room which was used as the instrument and working area during the test. Both doors were kept closed when the class was in session. The east side wall was a solid interior partition wall with classroom on the opposite side. A schematic of the room is shown in Figure 13, and a window section in Figure 14. Eight fluorescent lighting fixtures of four 40 W tubes each were hung 2 feet (0.61 m) from the ceiling. Excluding the ceiling beams, columns and the laboratory benches, the room had a net volume of 7,860 ft^3 (223 m^3). Two 9.25 inch (23.5 cm) by 13.25 inch (33.7 cm) ventilation exhaust grilles, each connected to a roof-top exhaust fan with a total design flow rate of 560 cfm (.264 m^3/s), were located just above the floor level near the south door and in the ceiling near the south column, respectively (Figure 13). Photographs of the grilles are shown in Figures 15 and 16. Fin-tube type radiators were located below the whole length of the window sill. The steam flow was controlled by a thermostat located at the mid-height of the south column.

The school class schedule was from 8:30 a.m. to 2:50 p.m., with two 15-minute home-room periods at the beginning and end of the school day and eight 40-minute regular class periods with 4 minutes between each period for the changing of classrooms. Students came into the classroom one minute before the beginning of a period and left the room at the end of a period. The exhaust fan system was turned on at 6:45 a.m., run throughout the day, and turned off at 4:30 p.m. Because of the mild spring weather, the boilers were run only 2 hours in the morning before the classes started.

The weather conditions during the 4-day test period were generally mild with a daily temperature range from 40 °F to 70 °F (4.8 to 21.4 °C). The dry-bulb temperature, relative humidity, and wind speed of the 4-day test period are shown in Figures 17 through 19. These data were obtained from the Weather Bureau of New York City.

1 ft = 3.048×10^{-1} m

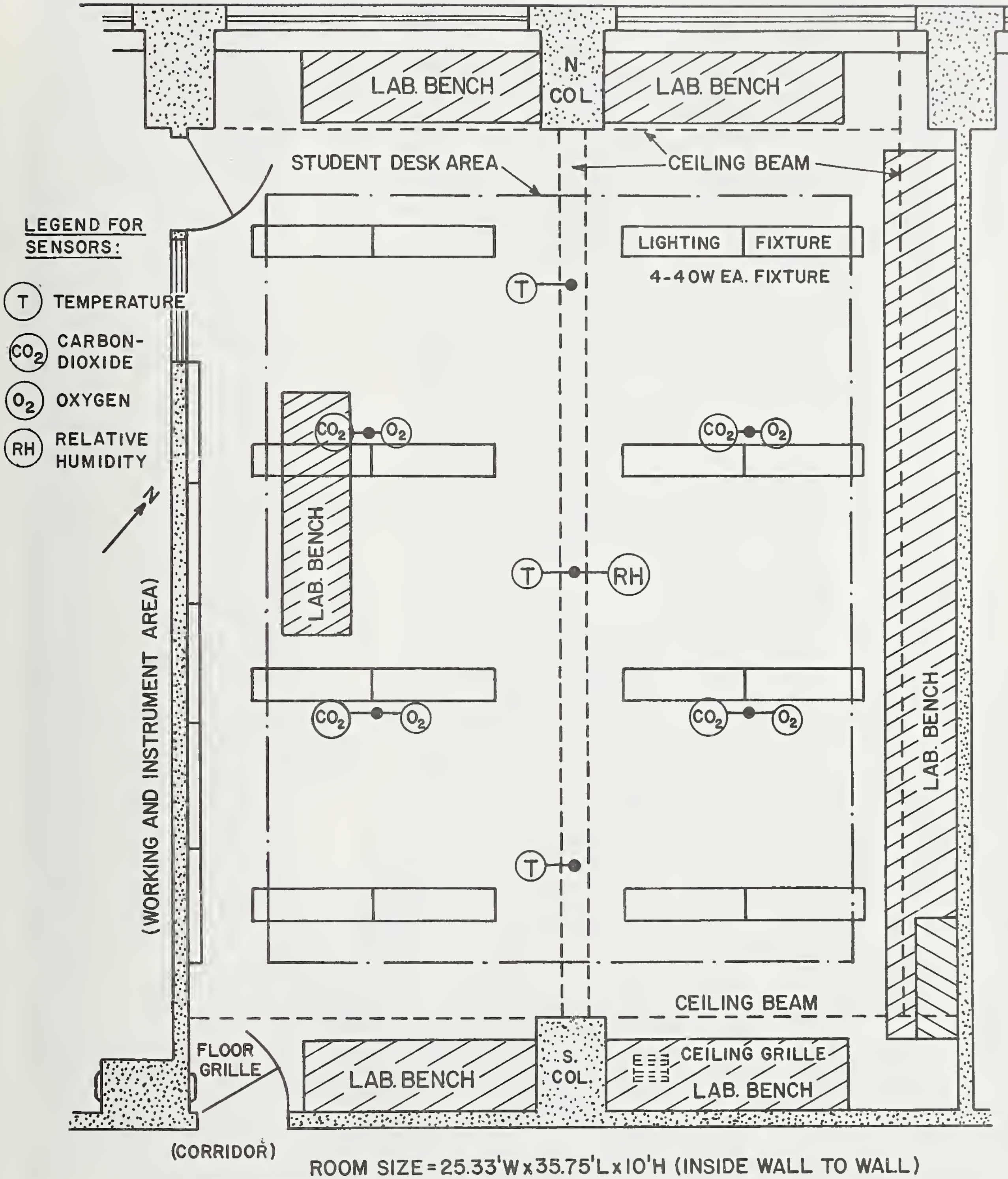
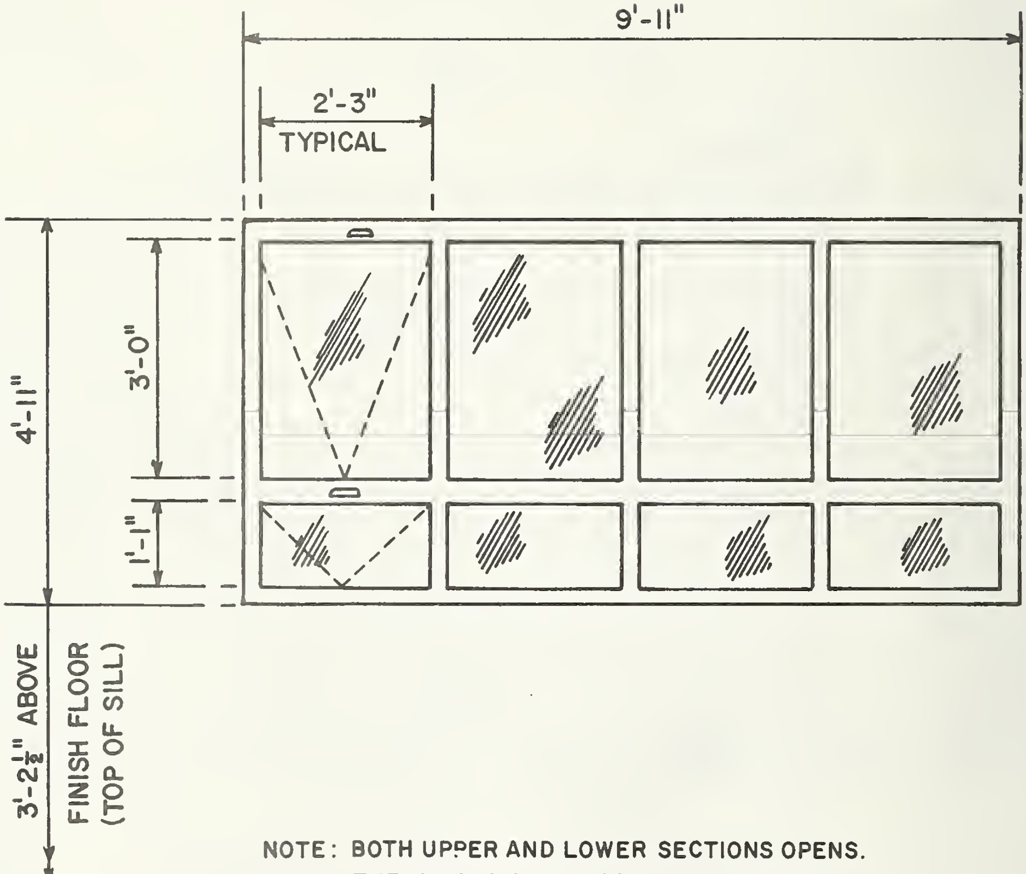


Figure 13 Schematic of the Classroom in School No. 10 Used for the Ventilation Test

1 in. = 2.54 cm
1 ft = 3.048 x 10^{-1} m



NOTE: BOTH UPPER AND LOWER SECTIONS OPENS. THE HINGES ARE LOCATED AT BOTTOM WITH PULL HANDLE AT TOP. WINDOW FRAMES ARE STEEL, AND THE GLAZING IS SINGLE PANE.

Figure 14 Schematic of a Window Section of the Ventilation Test Classroom

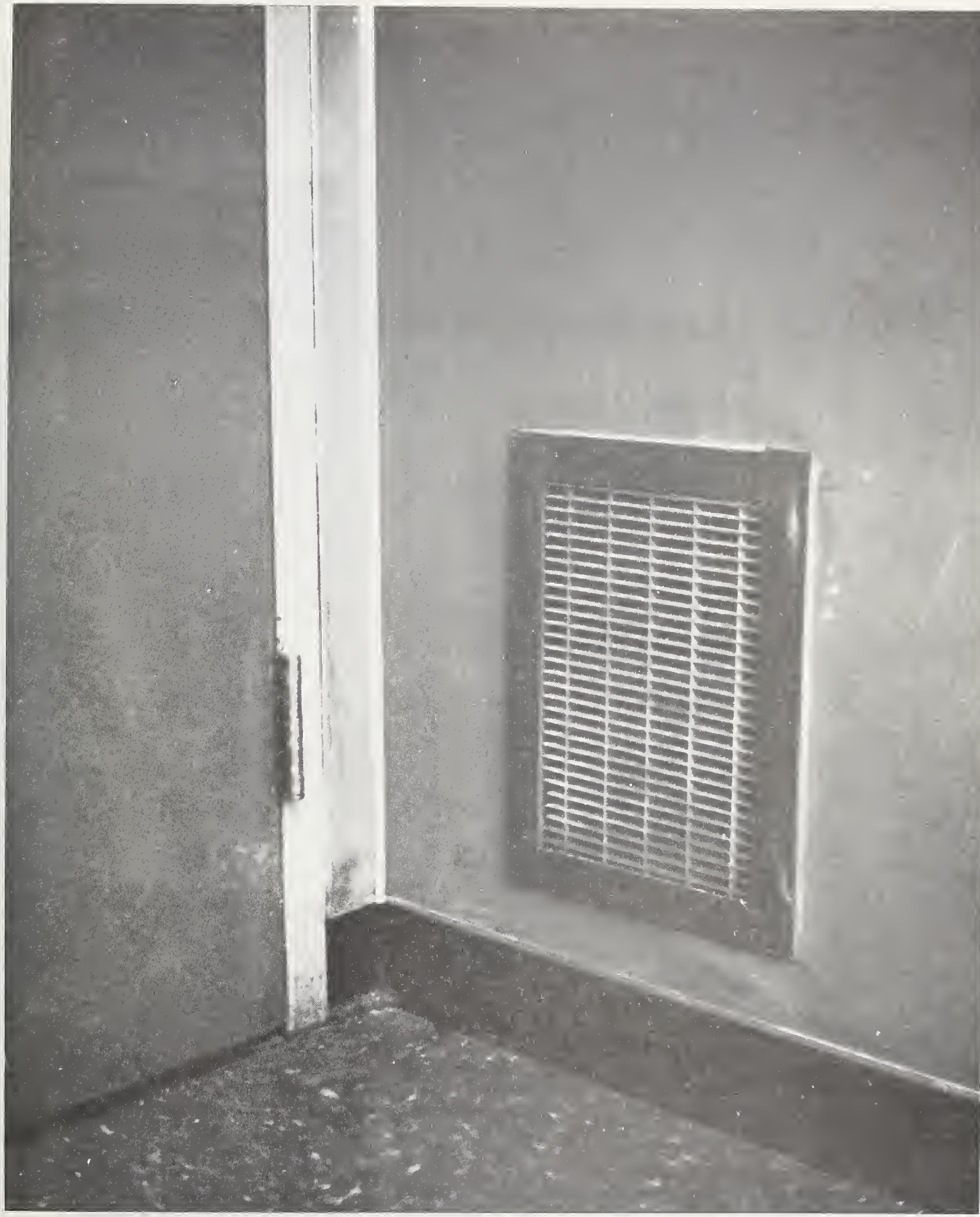


Figure 15 Photograph of the Floor Exhaust Grille in the Test Classroom

Figure 16 Photograph of the Ceiling Exhaust Grille in the Test Classroom

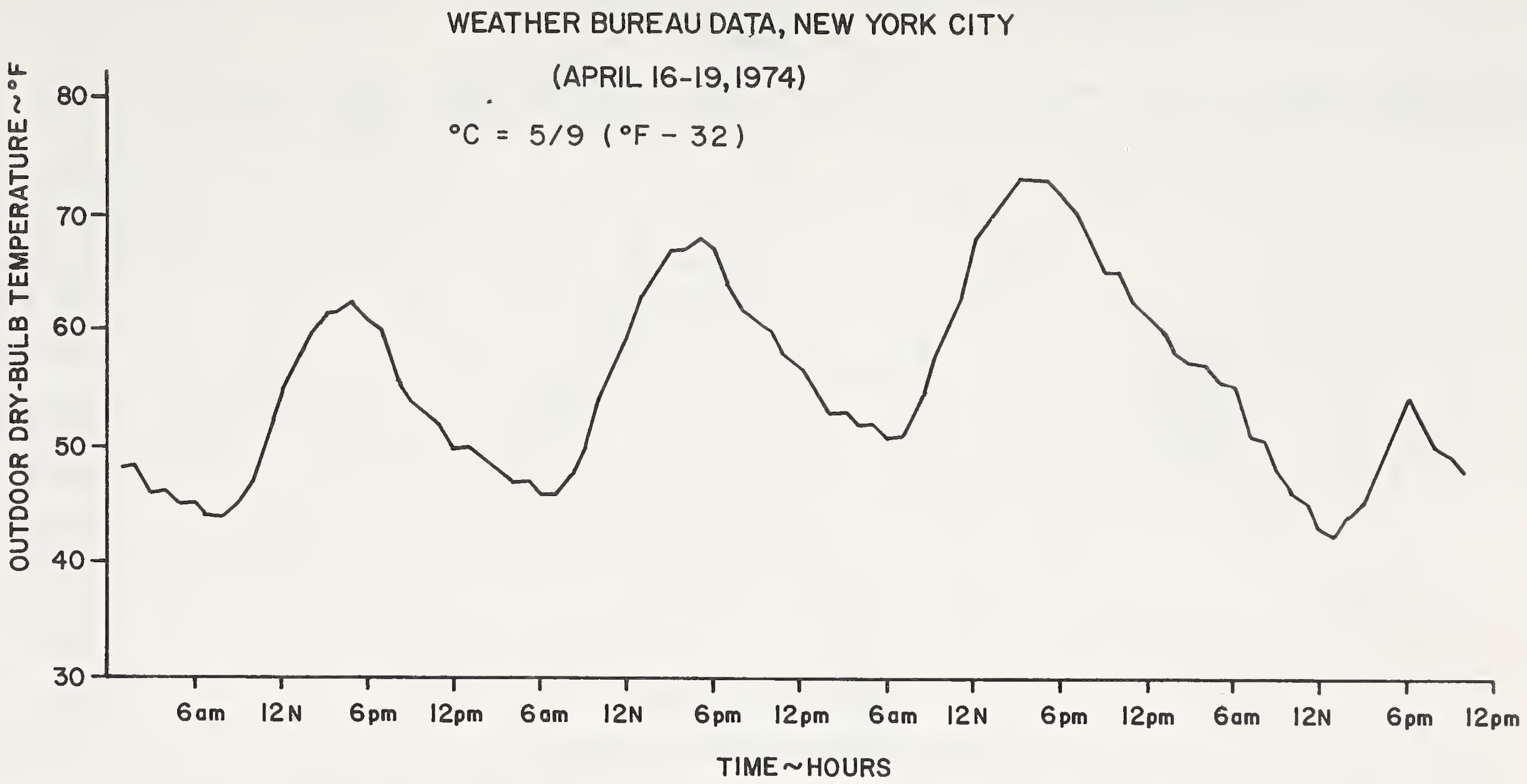


Figure 17 Variation of the Outdoor Dry-Bulb Temperature During the 4-Day Ventilation Test Period

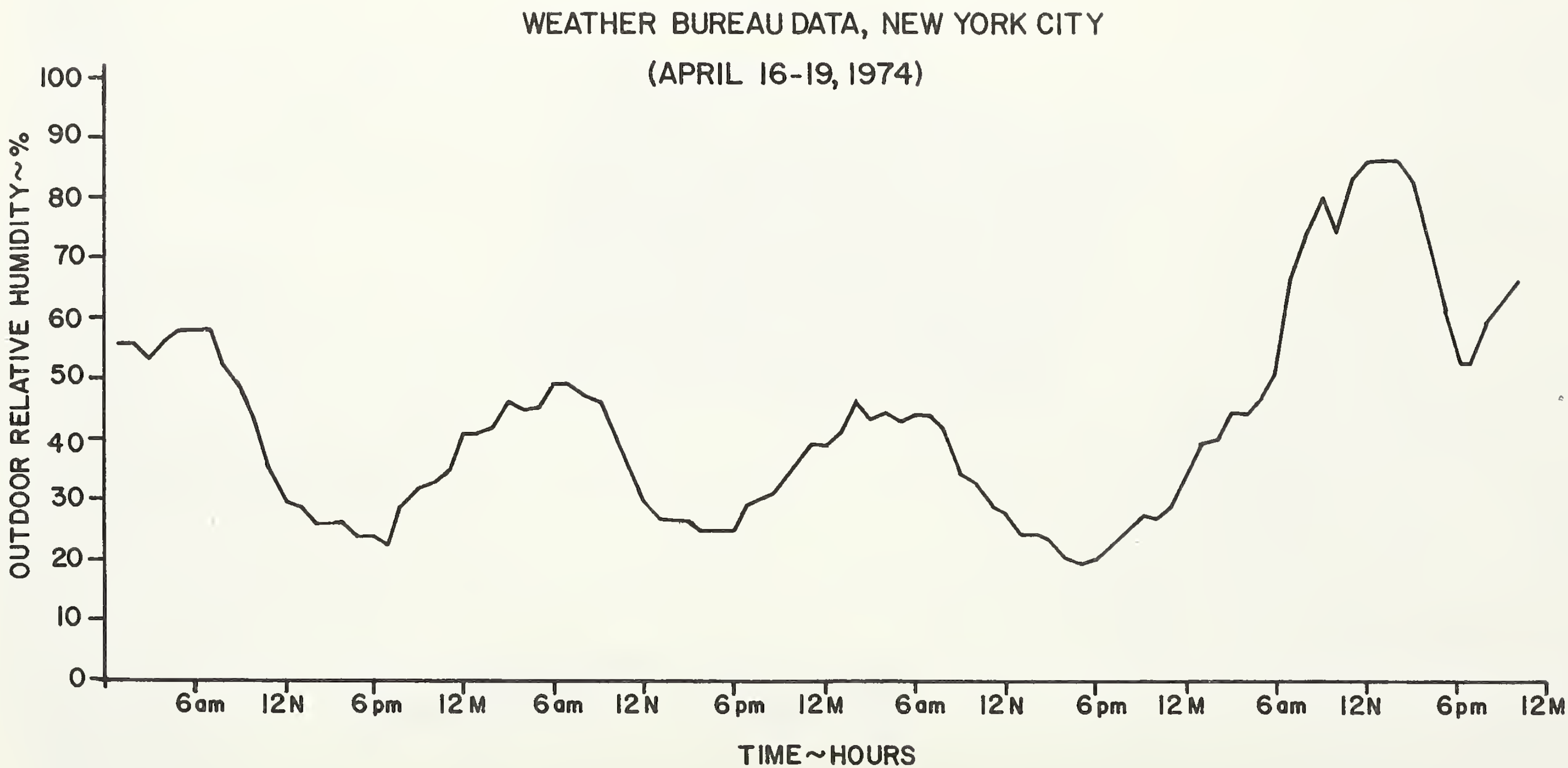


Figure 18 Variation of the Outdoor Relative Humidity During the 4-Day Ventilation Test Period

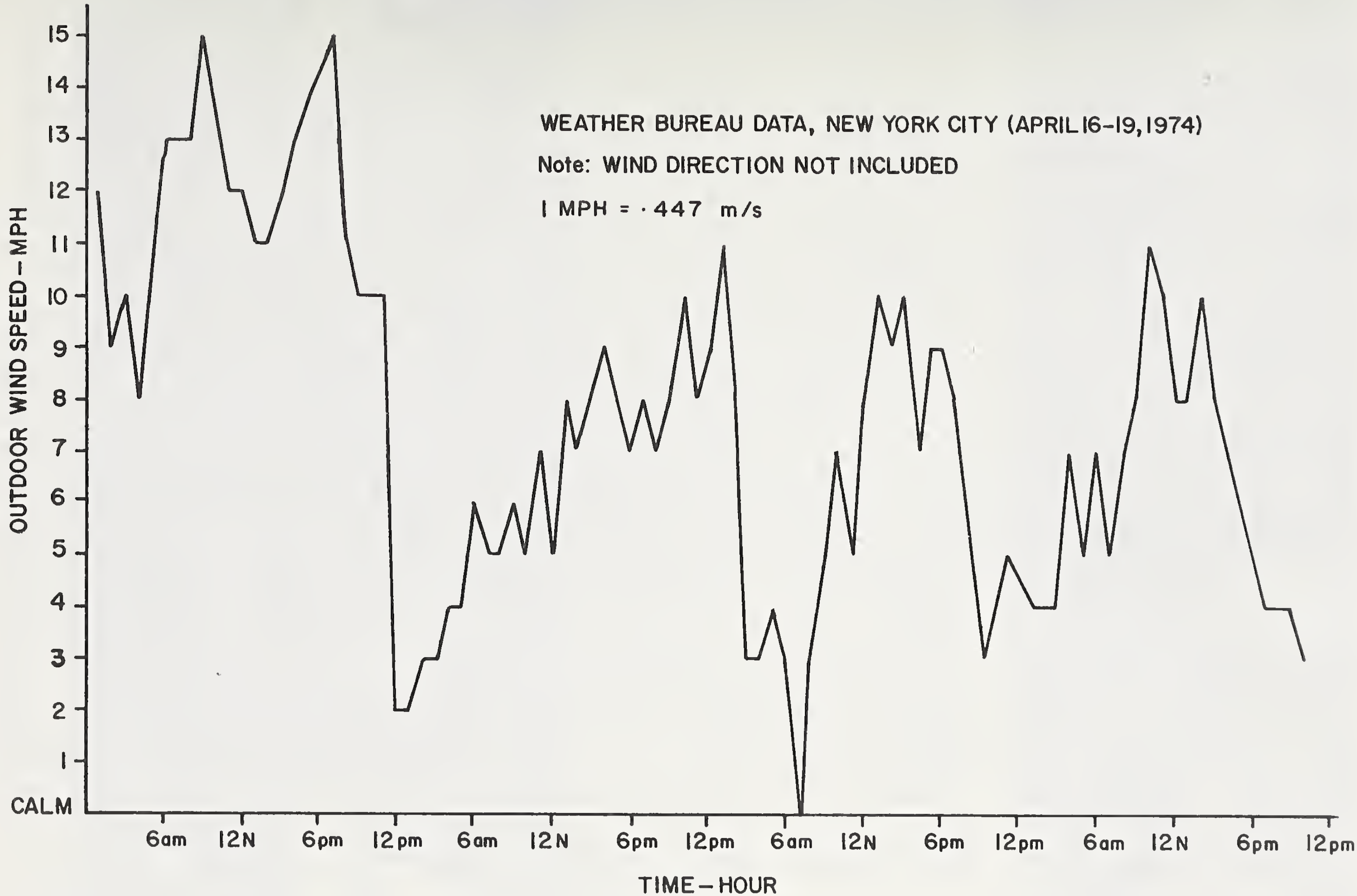


Figure 19 Variation of Outdoor Wind Speed During the 4-Day Ventilation Test Period

4.3 Test Setup and Instrumentation*

Temperature, relative humidity, CO_2 concentration, O_2 concentration, and air infiltration rate were the quantities measured during the test. The locations of the sensors, measuring instruments, and recording device are described below.

a. Temperature: Three copper-constantan 24-gauge thermocouples were used to measure the indoor temperature variations during the test. They were located along the center ceiling beam with one at the center of the room and the others 5 feet (1.52 m) from the north column and south columns, respectively. These 3 thermocouples were suspended from the ceiling beam 5.75 feet (1.75 m) above the floor. The locations of the 3 thermocouples are indicated by the dark circle and the symbol T in Figure 13. One Dewar bottle with a mixture of water and crushed ice was used as the ice-point reference for the thermocouples. The millivolt output of the thermocouples was recorded on a Strip Chart Recorder. The output of the thermocouple located at the center of the room was recorded continuously while the output of the other two were checked once every class period.

b. Relative Humidity: An American Instrument Relative Humidity Transducer (No. 15-7012) was used to measure the indoor relative humidity. The sensor was suspended from the ceiling and located at the same location as the center thermocouple and is represented by the symbol RH in Figure 13. A photograph of the RH sensor and the center thermocouple as installed is shown in Figure 20. The millivolt output from the sensor was recorded continuously on a Strip Chart Recorder. The accuracy of the humidity sensor was checked at selected levels in the range of 10 to 90 humidity using standard salt solutions and was found to have an accuracy of ± 2 percent.

c. Carbon Dioxide Concentration: At the stations indicated in Figure 13, four lengths of 1/4 inch (0.64 cm) plastic tubes were suspended over the middle four lighting fixtures to collect air samples from the classroom. The two in the front of the room were located 6 feet (1.83 m) away from the chalk board (west wall), and 13 feet (3.96 m) from the north and south walls, respectively. The two in the back of the room were located 7 feet (2.13 m) from the back wall (east wall) and 13 feet (3.96 m) from the north and south walls, respectively. The ends of the sampling tubes were 6 feet (1.83 m) above the floor. The 4 tubes converged into a junction which was in turn connected to a diaphragm type vacuum pump. The output of the vacuum pump was connected to a MSA LIRA 300 Infrared CO_2 Analyzer. The millivolt output of the analyzer was recorded on the second channel of the Strip Chart Recorder. The analyzer was calibrated before the test, and was checked twice a day with 384 parts per million CO_2 concentration standard reference gas, and the zero setting was checked at the same time with pure nitrogen gas.

d. Oxygen Concentration: Sample gas from the room collected through the plastic sampling tubes through the vacuum pump was also connected to a Bacharach Instrument Company Model 514-010-00 continuous Electrolytic Oxygen Detector Cell. The millivolt output from the cell was recorded on the second channel of the other Strip Chart Recorder. The cell was calibrated before the test and was checked twice a day with a 20.92 percent oxygen concentration standard reference gas, and the zero setting was checked at the same time with a pure nitrogen gas.

e. Flow Rate Through the Exhaust Grilles: Flow rate through the exhaust grilles was measured with a vane anemometer at the center and at 4 points located two inches (5.08 cm) from the sides along the center lines of the grilles. After the test, one grille was brought back to NBS and the flow rate through

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* Commercial instruments are identified in this report in order to adequately specify the experimental procedure. In no case does such identification imply recommendations or endorsement by the National Bureau of Standards, nor does it imply that the equipment identified is necessarily the best available for the purpose.

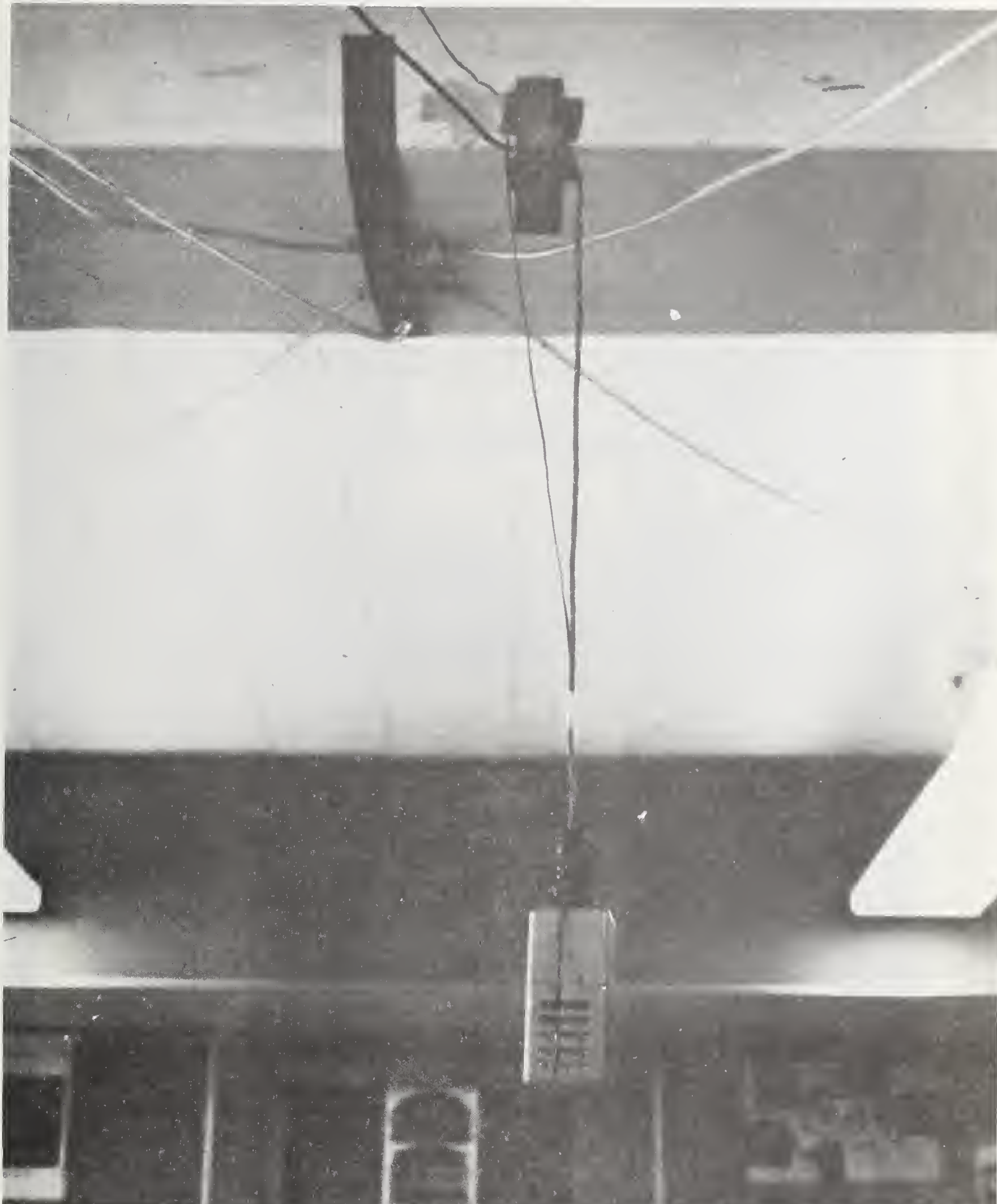

Figure 20 Photograph of the Relative Humidity Sensor and Thermocouple Setup in the Test Classroom

the grille was measured by the vane anemometer which was calibrated in the NBS air filter flow-test chamber.

f. Room Air Change Per Hour: The ventilation rate of the classroom under four different exhaust conditions was measured by the SF_6 tracer dilution method. A brief description of the principle of the method is given in the Appendix. These measurements were conducted at the end of each school day after the students had left the school.

The test was conducted under three different exhaust flow rate conditions. They were: (1) normal operation condition with both grilles open, (2) one exhaust grille (ceiling grille) blocked by taping a plastic sheet over the opening, and (3) both exhaust grilles blocked. In addition, an SF_6 tracer gas measurement for room air change rates was conducted when the ventilation system in the entire school building was shut off. This measurement was to determine the rate of air infiltration under natural conditions. It should be pointed out that the room air changes per hour with both grilles blocked and ventilation system operating was not the same as the natural rate of air infiltration with the ventilation system off, since the fans in the adjacent rooms draw air from the test room through the opening under and around the door via the corridor. The operation of the ventilation system creates a negative pressure difference between the test room and outside and increases the air change rate over the value caused by natural infiltration alone.

Figure 21 is a photograph of the setup in the test classroom showing the location of the thermocouples, relative humidity sensor, and the sample air intake tubes. Figure 22 shows the instruments used for the test which were located in the teacher's preparation room adjacent to the test classroom. The equipment in the front of the photograph is the reference calibration gas container and the SF_6 tracer gas equipment. The instruments on the counter are (from left to right) the vacuum pump, CO_2 Analyzer, Oxygen Detector Cell, Dewar Flask, Strip Chart Recorder, Thermocouple Switch Box, Strip Chart Recorder, Digital Voltmeter, and D. C. Power Supply.

4.4 Discussion of Test Results

The results of the test under the different ventilation conditions are shown in Figures 23 to 34.

a. Temperature and Relative Humidity: Figures 23 through 25 show the variation of the room temperature during a class period (40 minutes) under the three test conditions: (1) both grilles open, normal operation, (2) ceiling grille blocked, and (3) both grilles blocked. The time scales were from the beginning of the class period to the end of the period. It is seen that the temperature rose at the beginning of the period when the lights were switched on and students entered the room. However, the temperature remained within the range of 70 °F to 80 °F (21.4 to 27.0 °C) throughout the class period. Figures 26 and 27 show the variation of the indoor temperature and relative humidity during a school day under the most severe conditions tested; namely, when both exhaust grilles were blocked off. (The outdoor temperature and relative humidity are also plotted on the graphs.) It is seen that the presence of students and lighting caused the temperature to increase 5 °F (2.8 °C) and the relative humidity to increase 5 percent. However, both the temperature and relative humidity stayed within the comfort region of 70 to 80 °F (21.4 to 27.0 °C) and 20 to 30 percent. The variations of temperature and relative humidity under the other two less severe conditions were similar to Figures 26 and 27 and are not shown. However, it should be pointed out that the outdoor conditions over the 4-day period were very mild. Under a more severe outdoor condition--for example, hot and humid conditions--the blocking of the grilles and the corresponding reduction in air movement might cause the room air to become stuffy.

Figure 21 Photograph of the Test Setup in the Classroom for Ventilation Tests

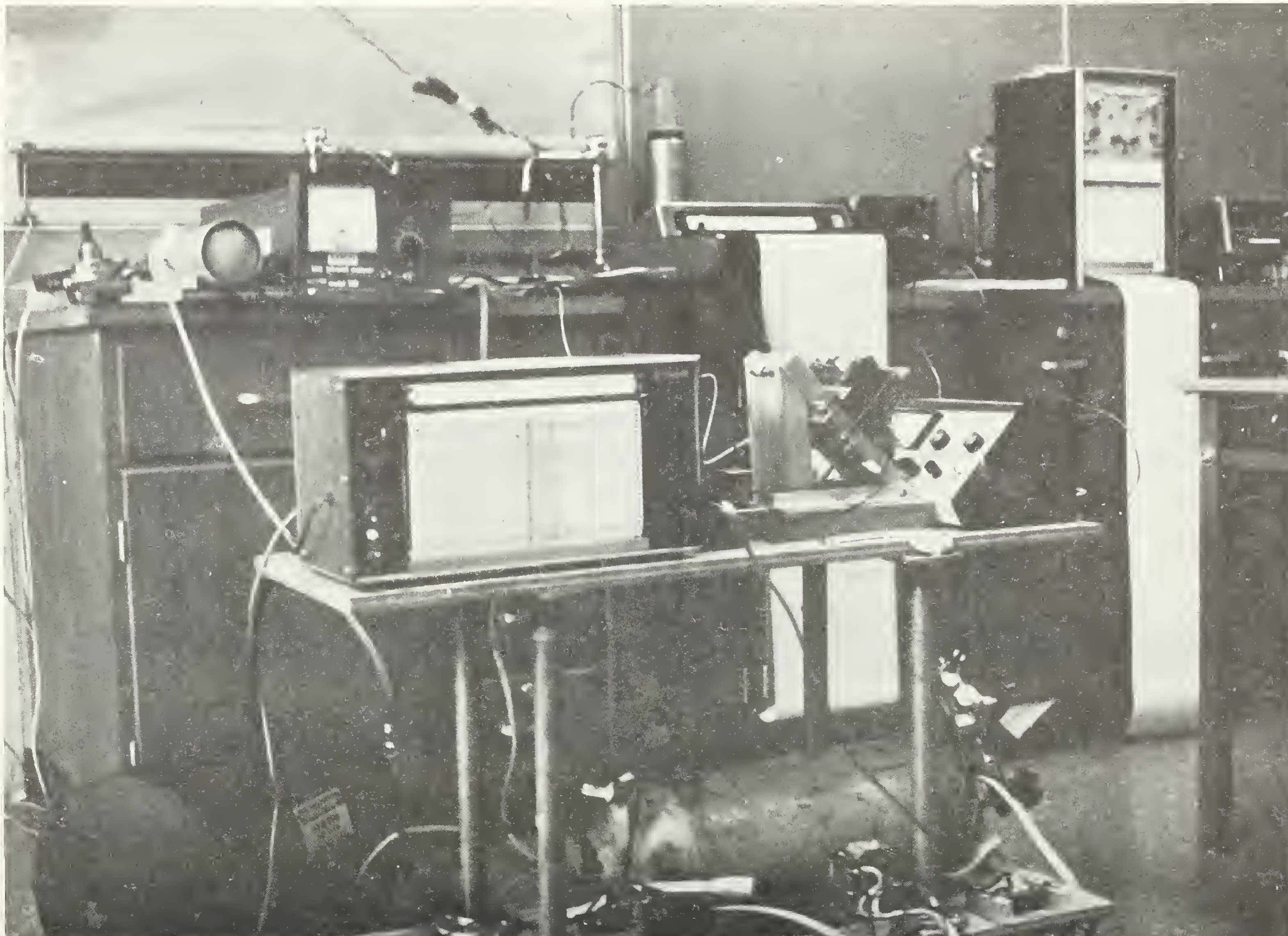

Figure 22 Photograph of the Instruments Used in the Ventilation Tests

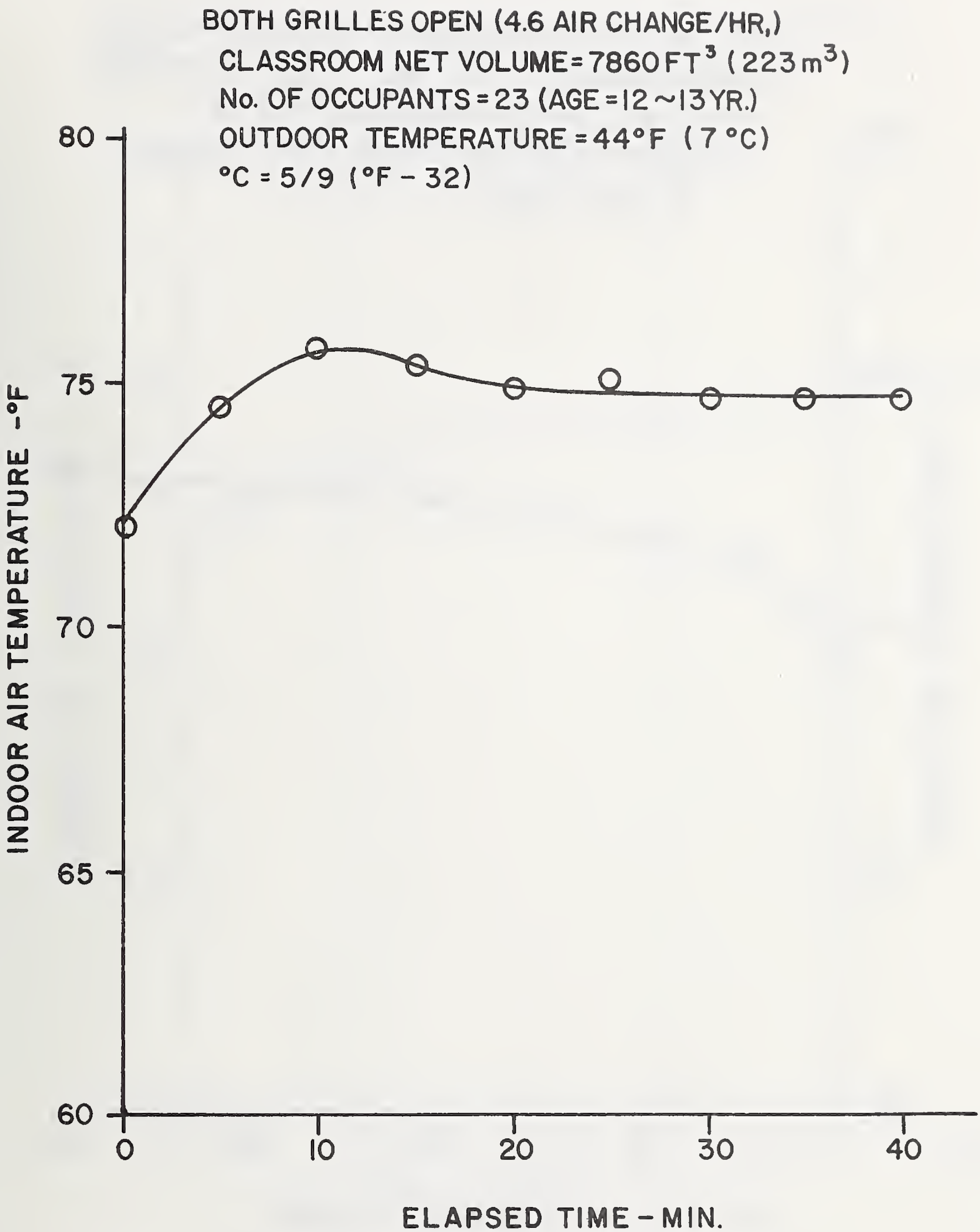

Figure 23 Indoor Air Temperature Variation During One Class Period (Normal Condition, Both Grilles Open)

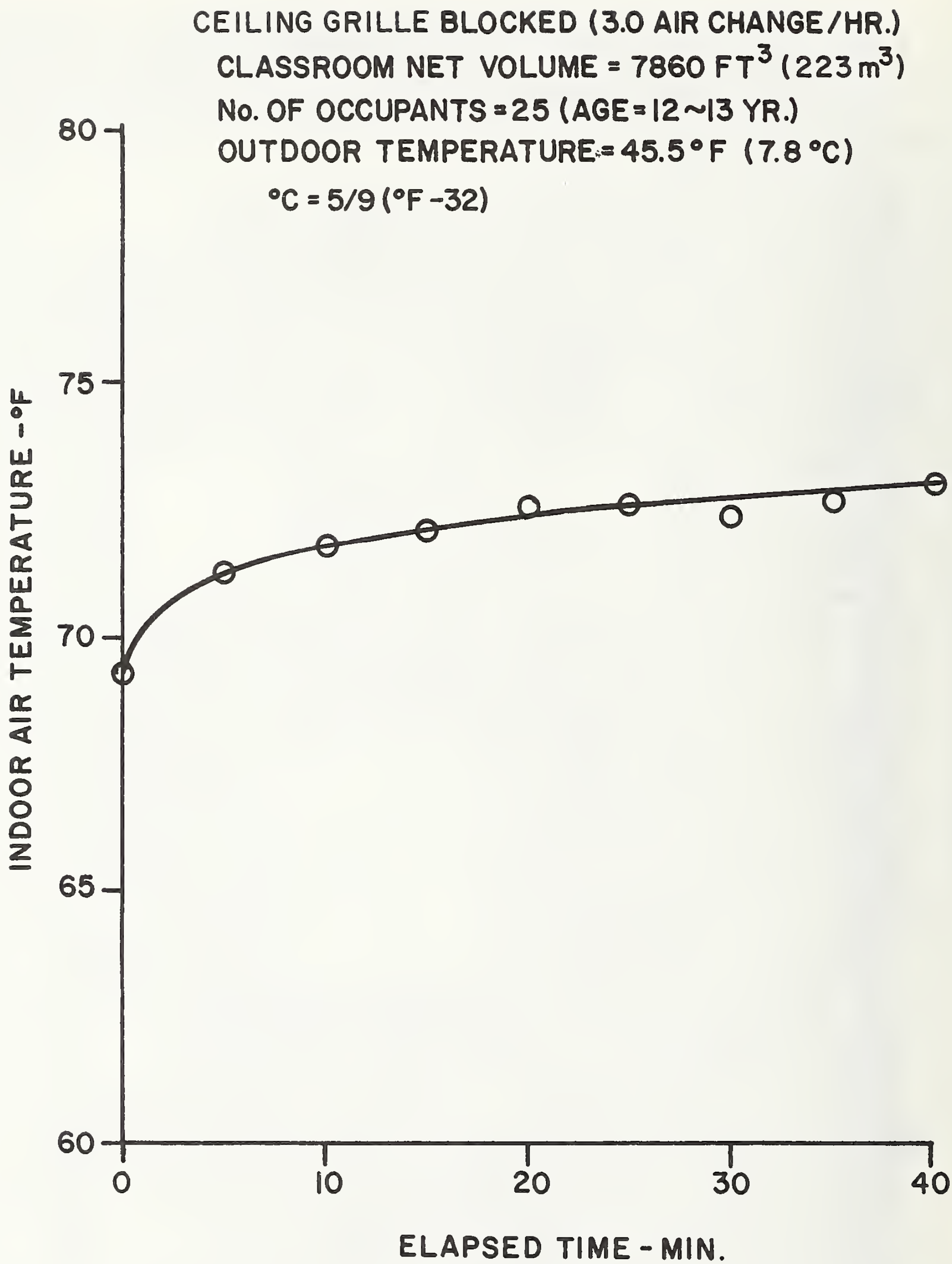

Figure 24 Indoor Air Temperature Variation During One Class Period (Ceiling Grille Blocked)

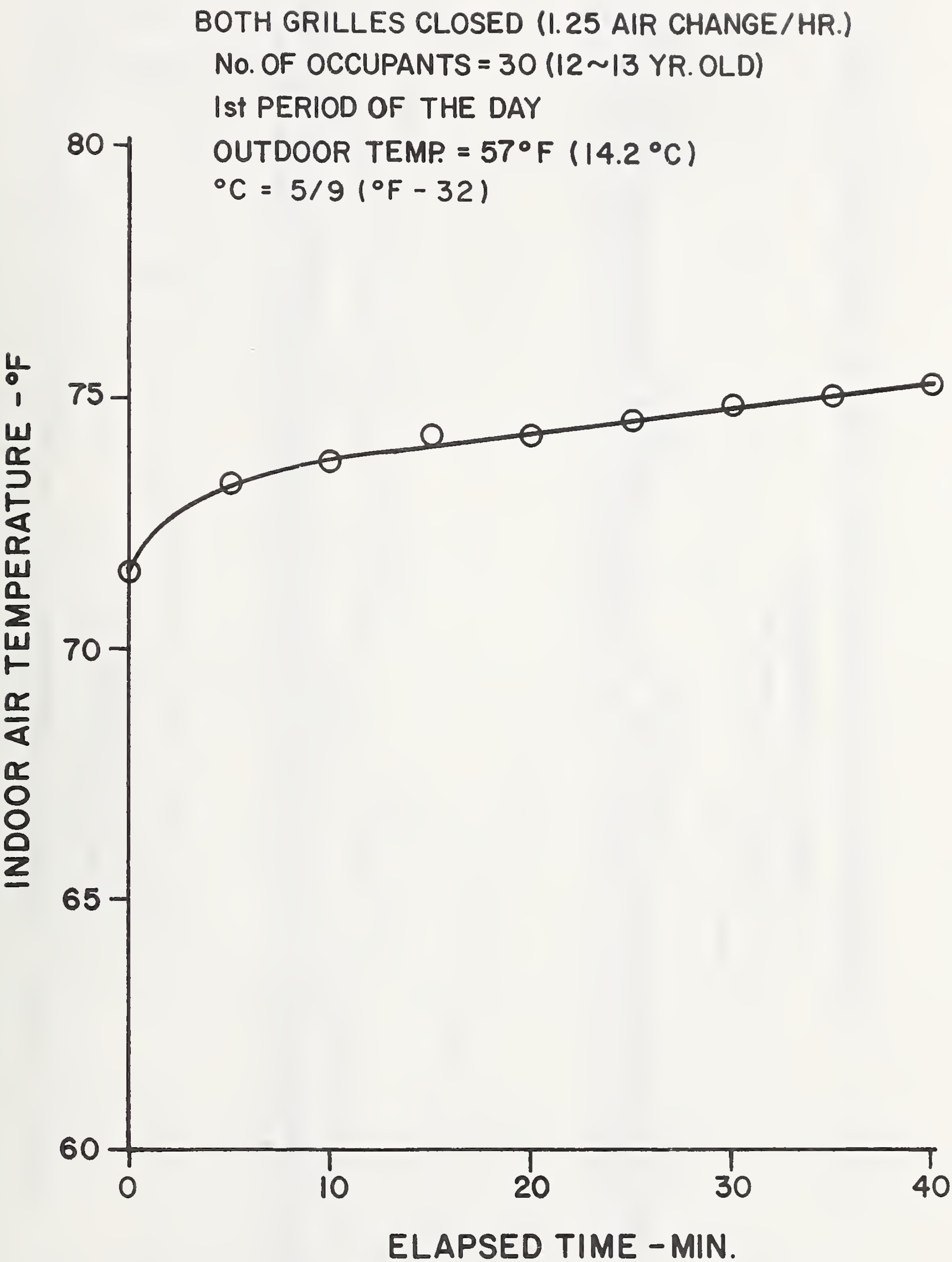

Figure 25 Indoor Air Temperature Variation During One Class Period (Both Grilles Blocked)

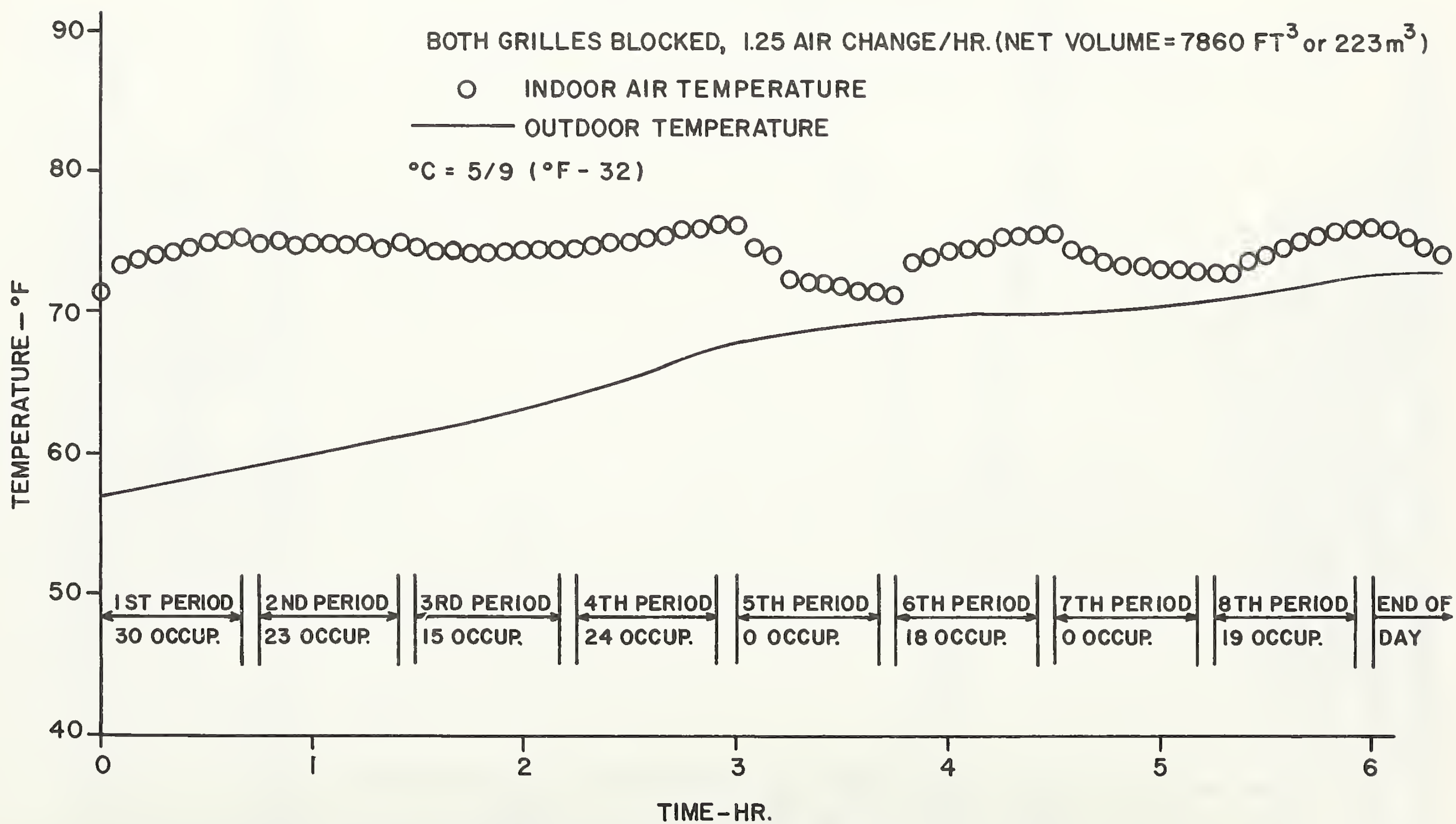

Figure 26 Variation of Indoor Air Temperature During One School Day (Both Grilles Blocked)

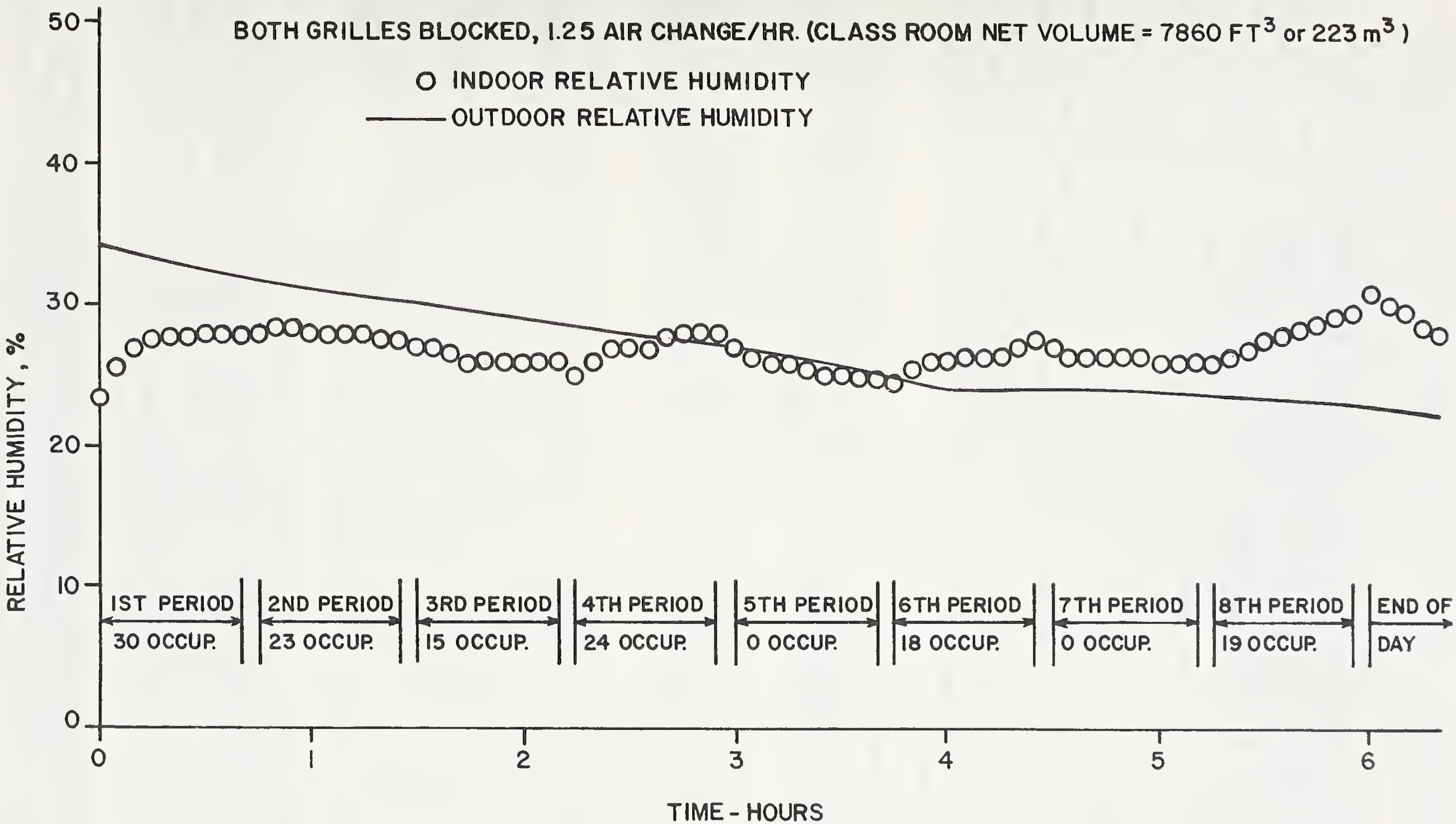

Figure 27 Variation of Indoor Relative Humidity During One School Day (Both Grilles Blocked)

b. CO2 Concentration: Figures 28 through 30 show the buildup of CO_2 concentration under the three test conditions. The periods chosen for these graphs are those which had no students in the classroom during the preceding one or two periods so as to show the rate of CO_2 buildup from near normal concentration conditions (0.05 to 0.07 percent). The air change rate under the three test conditions as measured by the SF_6 tracer gas technique was 4.6 air changes per hour (both grilles open, normal operation), 3.0 air changes per hour (ceiling grille blocked), and 1.3 air changes per hour (both grilles blocked), respectively. It is seen from Figures 28 to 30 that the levels of CO_2 concentration under all three conditions were far below the 0.5 percent safety limit cited at the beginning of this section. This is expected, since in terms of cfm per student the most severe conditions of 1.3 air changes per hour with the 30 occupants in the test room (net volume of 7,860 ft^3 or 223 m^3) still gave a value of 5.5 cfm/student (2.60×10^{-3} m^3/s per student) which was higher than the 4 cfm/student (1.89×10^{-3} m^3/s per student) specified in reference 9. However, Figures 28 to 30 do show that when the air changes per hour were decreased, it took a longer time for the CO_2 concentration to reach a near steady-state level. The steady-state level increased as the ventilation rate was decreased. Since the rate of CO_2 production for an adult is higher than for a child, it is expected that the steady-state CO_2 concentration level would be higher for students of high school age, even though the safety limit of 0.5 percent still would not be exceeded because the ratio of CO_2 production for a 12-year-old child to that of an adult is about 0.7.

Figure 31 shows the variation of the CO_2 concentration for a school day when both grilles were blocked. It is seen that the maximum concentration level reached was 0.16 percent by volume, and the level decreased rapidly whenever there was an unoccupied period. The patterns for the other two test conditions were similar and are not shown.

Figure 32 shows the level of CO_2 concentration at the end of a class period as a function of the number of occupants. As would be expected, the level increased as the number of occupants increased. The scattering in the data points might be due to differences in age and activity level for the students during different class periods.

It is also possible to estimate ventilation rates from the rate of decay of CO_2 concentration. However, the air entering the space has a finite concentration, and this must be taken into consideration, as indicated in the Appendix. If the outside air entering the room is assumed to have a concentration of 0.05 percent CO_2, the rate of decay shown in Figure 33 corresponds to 4.1 air changes per hour compared with 4.6 air changes per hour obtained by using SF_6 dilution. There is still residual curvature in the concentration vs. time plot when the concentration is corrected for CO_2 in the incoming air. This suggests that the rate of mixing of tracer with air does not keep up with the rate of ventilation (11). This is true especially at the higher ventilation rate. A similar analysis of the data in Figure 34 indicates an air exchange rate of 1.3 air changes per hour, compared with the same value obtained with SF_6.

c. O_2 Concentration: Under the three test conditions, no noticeable change in the the level of oxygen content in the test room was detected. This result was expected, since with the respiratory quotient (or rate ratio of CO_2 production to oxygen consumption) for a normal person being equal to approximately 0.83[10], an increase of 0.1 percent in CO_2 concentration results in a decrease of less than 0.2 percent in O_2 content in the room. This amount was an order of magnitude below the safety limit of 3 percent decrease from normal level, and was outside the range of accuracy of the detector cell used.

d. Exhaust Flow Rate Through Grilles and Air Change Measurement: The total exhaust flow rates through the two grilles were measured by a vane anemometer, and the air change rates of the room were determined by the NBS SF_6 Tracer Gas Technique, for 4 different test conditions, as listed below:

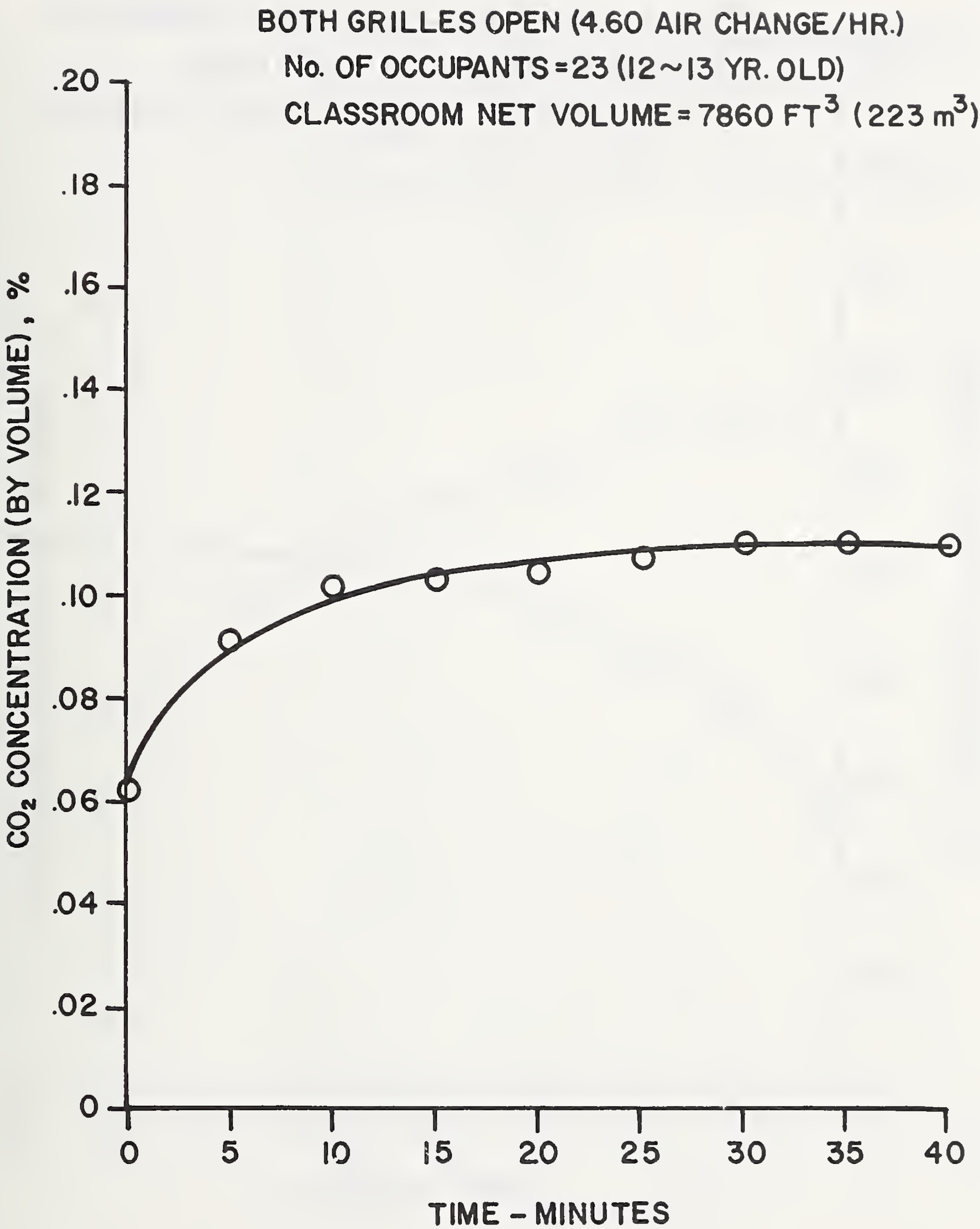

Figure 28 Variation of Indoor CO_2 Concentration During One Class Period (Normal Conditions, Both Grilles Open)

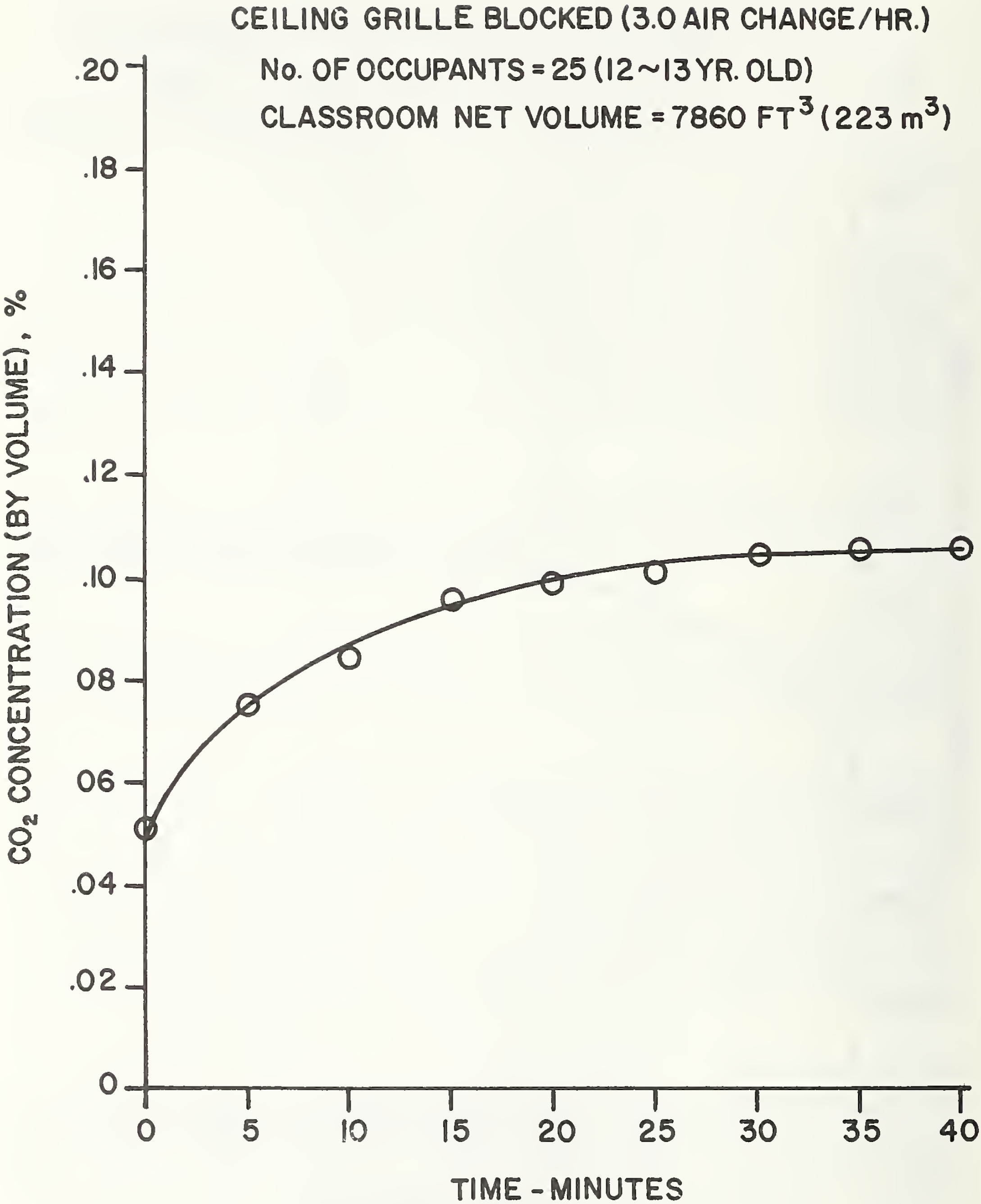

Figure 29 Variation of Indoor CO_2 Concentration During One Class Period (Ceiling Grille Blocked)

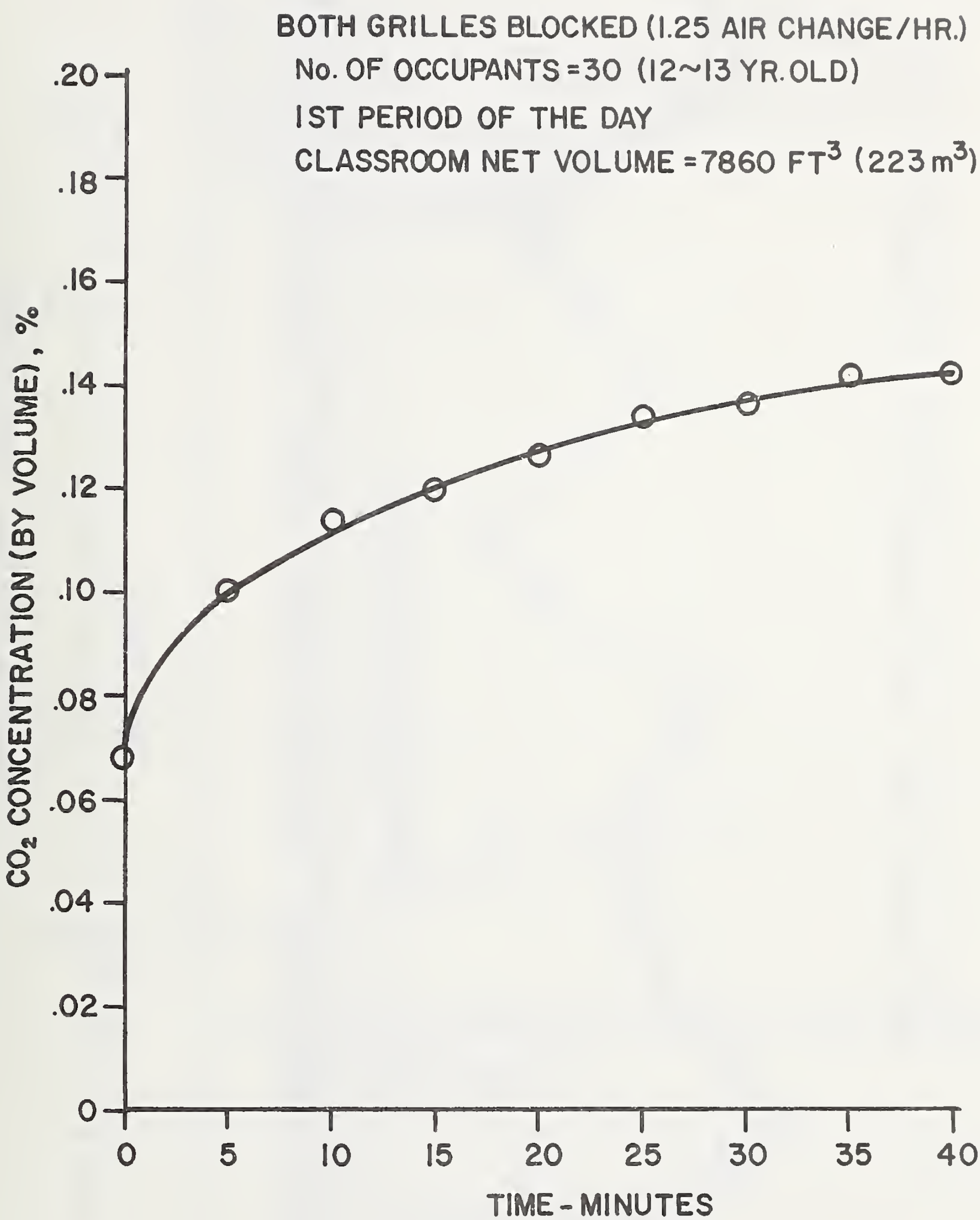

Figure 30 Variation of Indoor CO_2 Concentration During One Class Period (Both Grilles Blocked)

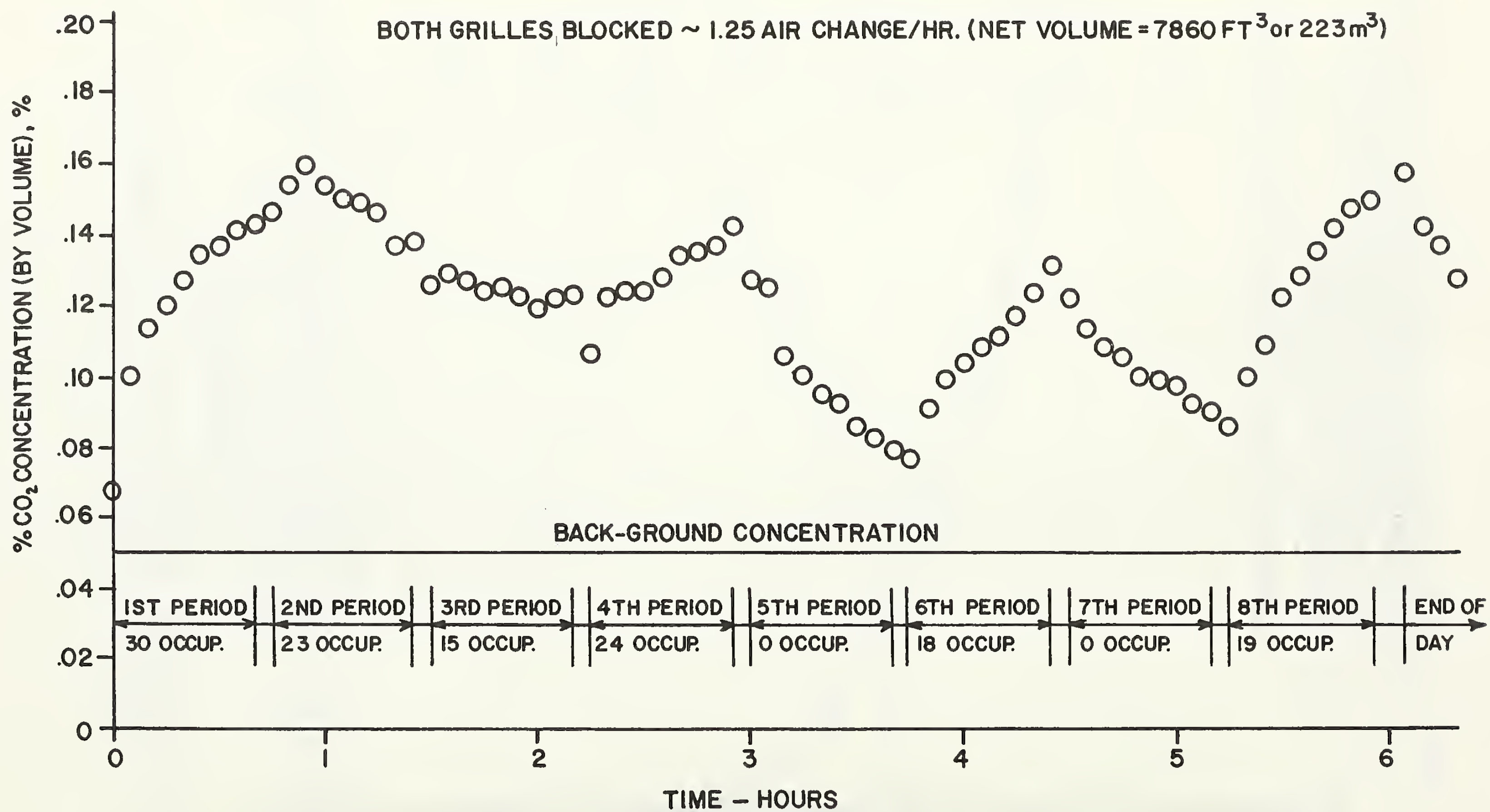

Figure 31 Variation of Indoor CO_2 Concentration During One School Day (Both Grilles Blocked)

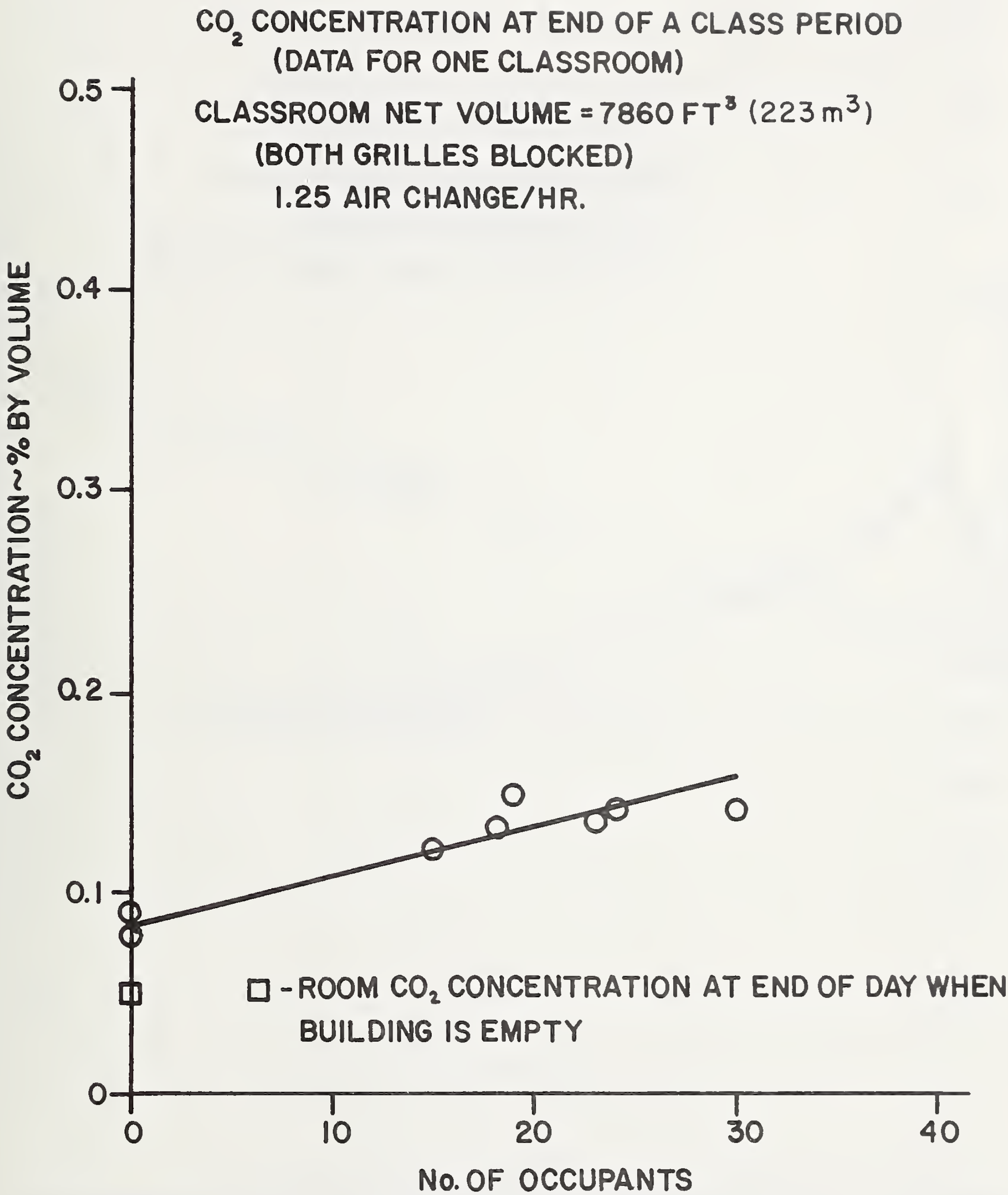

Figure 32 Steady-State Indoor CO_2 Concentration Level Vs. No. of Occupants

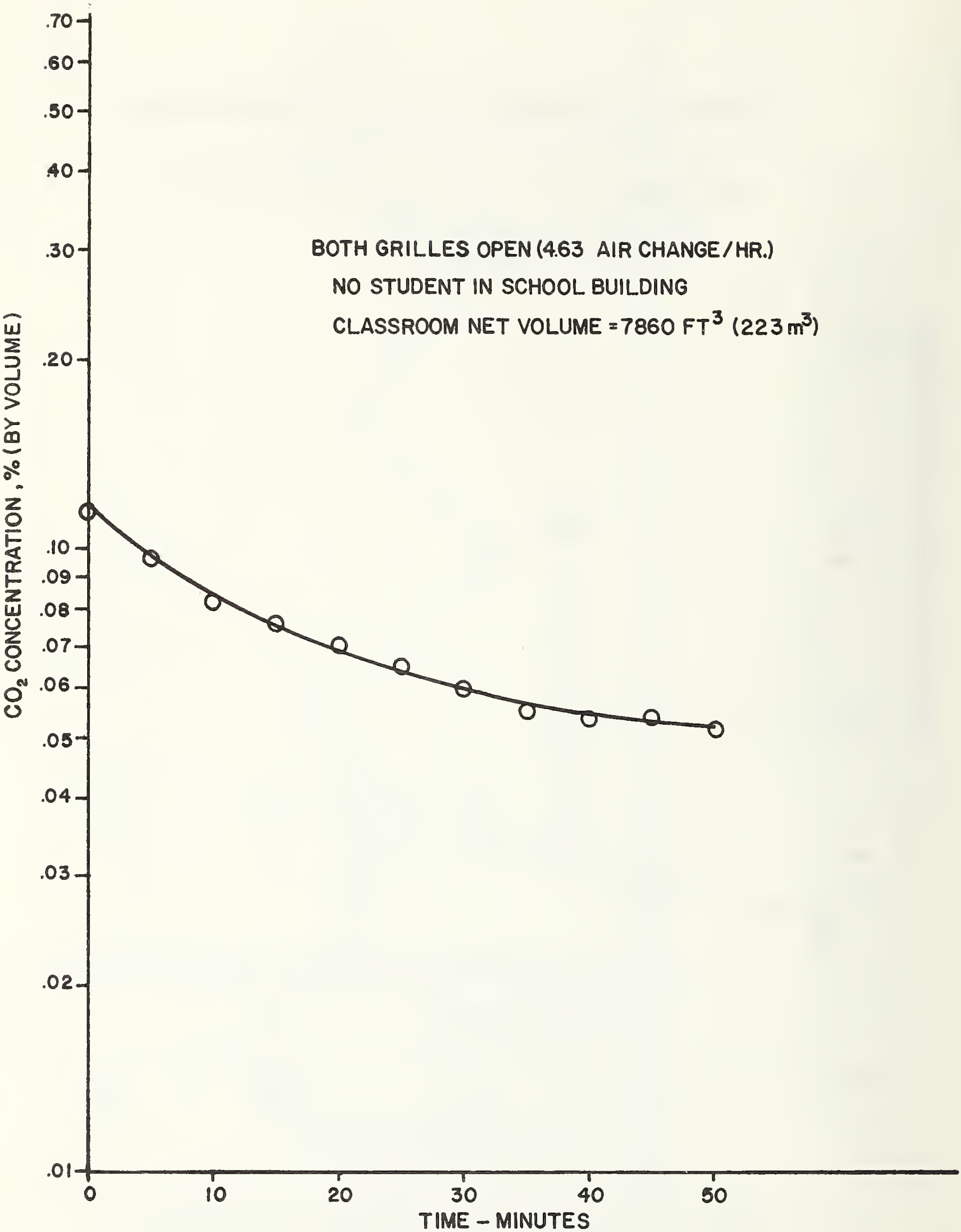

Figure 33 Decay of Indoor CO_2 Concentration in Empty Classroom (Both Grilles Open)

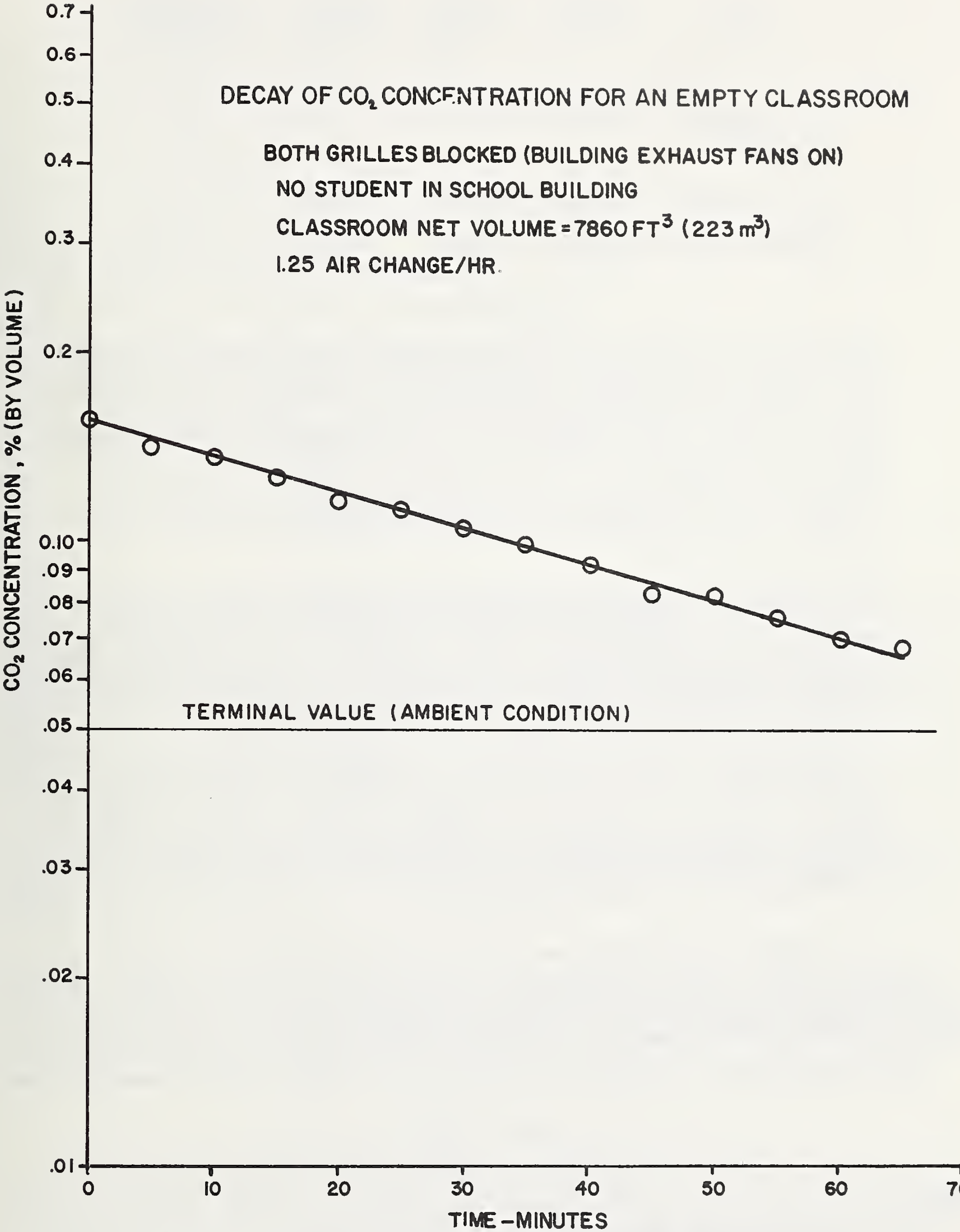

Figure 34 Decay of Indoor CO_2 Concentration in Empty Classroom (Both Grilles Blocked)

Test Conditions	Both Grilles Open	Ceiling Grille Blocked	Both Grilles Blocked	Building Ventilation System Off
Air Change/Hour (SF_6 Tracer)	4.6	3.0	1.3	0.23
Grilles Exhaust Rate (Vane Anemometer)	440 cfm (0.208 m^3/s)	240 cfm (0.113 m^3/s)	0 cfm (0 m^3/s)	0 cfm (0 m^3/s)

It is seen from the above that when both the grilles were blocked but with the building ventilation system in operation, the test room still had an air change rate 5 times greater than the rate when the entire building ventilation system was shut off. It is therefore emphasized here that the results of CO_2 concentration and oxygen content discussed in the previous subsections are not applicable to a classroom or a building where no mechanical ventilation system is provided for the building and the only means of air change is by natural air infiltration. The natural air change rate would be higher in winter time due to larger temperature differences between the indoor and outdoor air and due to higher wind speeds; however, it is doubtful that the increase would be as large as a factor of 5.

e. Observation of Students' Reaction During the Test Period: During the 4-day test period, the reactions of the students were observed by a research psychologist of the Sensory Environment Section of NBS. The psychologist sat in on classes and personally assessed the changing classroom environment. Student comments were noted, and changes in dress, posture, and conduct were observed. In addition, informal discussions were conducted with the teacher at the conclusion of each class period.

Throughout the test period, no differences in temperature, humidity, odor, or eye irritation were noted by the observer. No changes in student behavior were observed. The students showed some curiosity about the test setup and inquired as to the purpose of the experiment. However, no comments were made indicating a change in air temperature, or air quality. The teacher was informed of the changes in test condition at the beginning of each day, and was unable to detect any difference in the classroom environment.

4.5 Estimate of CO_2 Concentration Under Natural Air Infiltration Condition

To avoid the possibility of exceeding the safety limit of 0.5 percent CO_2 concentration in other classrooms not under observation and instrumentation, the most severe condition, in which the entire ventilation system of the building would be shut off, was not tested.

The CO_2 concentration in a room or a building can be estimated by the following equation:

$$Cr\,(t) = Cr_o + \left\{(C_o - Cr_o) + \frac{N\dot{G}}{VA_c}\right\} \{1 - \exp\,(-\,A_c t)\}$$

where

$Cr\,(t)$ = room concentration of CO_2 at time t

Cr_o = room concentration of CO_2 at time t = o

C_o = constant outdoor ambient CO_2

N = number of occupants in a room

$\dot{G}$ = average CO_2 volume rate of production/occupant

V = volume of room

A_c = air change rate

t = time

The assumptions for the above equation are:

1. constant outdoor ambient CO_2 concentration level
2. uniform CO_2 concentration throughout the room at any time
3. air change with ambient air at constant CO_2 concentration level only

Equation (1) can be rearranged to solve for $\dot{G}$, giving

$$\dot{G} = \frac{A_c V}{N} \left\{ \frac{Cr - Cr_o}{1 - \exp(-A_c t)} - (Co - Cr_o) \right\} \tag{2}$$

To obtain an average CO_2 production rate for the students in the test classroom, the test results of Figure 30 were used. From Figure 30, with $A_c = 1.3$, $N = 30$, $C_o = .0005$, $Cr_o = .00068$, $Cr = .00143$ at $t = .667$ hr, and $V = 7{,}860$ ft^3 (223 m^3), the value of $\dot{G}$ is computed by using equation (2). The result is $\dot{G} = 0.44$ ft^3/hr (3.46×10^{-6} m^3/s) per student. This is equivalent to about 540 grams per day which can be compared with 642 grams per day reported by Wang [12] for college students in an auditorium. In reference 9, the production rate of CO_2 for a standard seated adult was given as 0.75 ft^3/hr (5.9×10^{-6} m^3/s). Assuming the production rate of CO_2 for an eighth grader to be 70 percent of that for an adult, the value for $\dot{G}$ will be .525 ft^3/hr (4.13×10^{-6} m^3/s) which is in reasonably good agreement with the computed value based on test results.

Assuming $\dot{G} = .50$ ft^3/hr (3.93×10^{-6} m^3/s) for an average eighth grader, the steady-state concentration of CO_2 in the test classroom with 24 students and an outdoor ambient CO_2 concentration level of .05 percent was computed by equation (1) for various air change rates, and compared with the results obtained from the tests under the three test conditions. The results are shown in Figure 35.

From Figure 35, it is seen that the estimated and the measured results showed excellent agreement. Figure 35 also shows that for an air change rate of 0.25/hr, the CO_2 concentration in the test room with 24 students would reach a steady-state level of 0.65 percent which would be higher than the maximum safety limit of 0.50 percent. (It is therefore concluded that for a building without any mechanical ventilation and with the windows closed, natural air infiltration alone could not be relied upon to prevent the CO_2 concentration level from rising above the maximum safety limit.

5. Conclusions

Under the sponsorship of the National Science Foundation, an analysis on energy consumption and ventilation requirement for an urban school building in New York City was completed. The tasks involved in this project included (1) the selection of a norm in energy consumption for comparison with a future energy-efficient school, based on the actual electrical energy and fuel-oil consumptions of 19 existing schools, (2) a computerized energy analysis of one of the 19 schools that had an energy consumption close to the norm, in order to determine the pattern of energy consumption in the school, and (3) a ventilation test in a classroom to determine the effects of reduced ventilation rate on the general environment of the classroom.

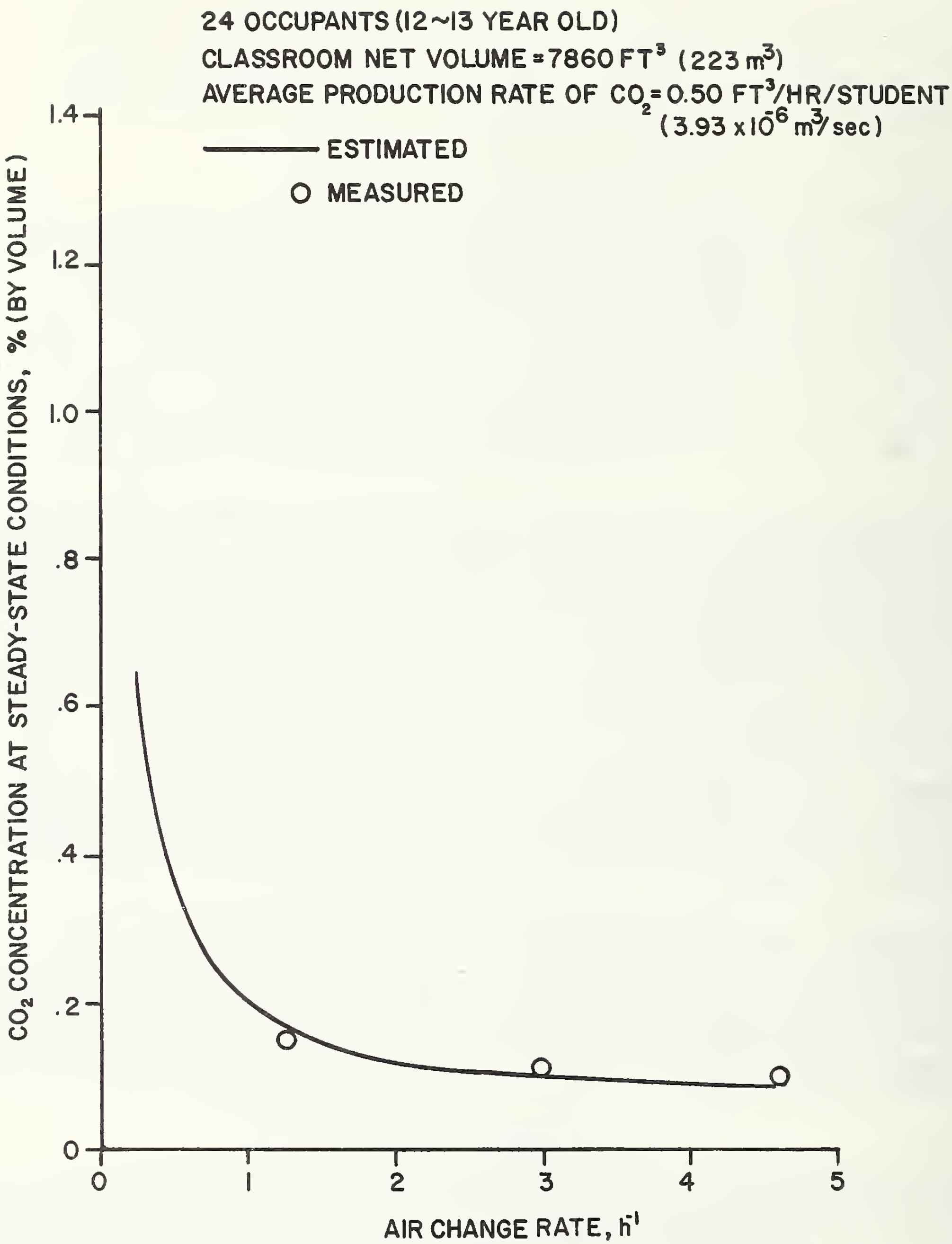

Figure 35 Estimated Steady-State CO_2 Concentration in a Classroom Vs. Air Change Rate

The electrical energy and fuel-oil consumption data of the 19 schools were provided by the Board of Education of New York City. It was found that when two somewhat atypical schools were omitted, the overall energy consumption of the other 17 schools varied by a factor of less than 2. The two atypical schools had a very high consumption rate. Omitting these two schools, the arithmetic values of 5,250 kWh and 417 gallons, both per 1,000 ft^2 gross area (2.03×10^8 J and .017 m^3 per m^2 of gross floor area) were chosen to be the average yearly electrical energy and fuel-oil consumptions of a typical school.

Based on the architectural drawings of the schools provided by the Board of Education, it was found that most of the schools in New York City were of the cavity-wall type construction, 3 stories high, single-pane glass with a window to exterior wall area ratio ranging from 0.3 to 0.6 for a typical classroom. Ventilation was provided for the classrooms by top exhaust fans on the roof, and space heating was provided by fin-tube radiators under window sills using low pressure steam. Except for a few schools, most schools had no space cooling equipment.

The computerized energy analysis was performed on one of the 19 schools. The school had a configuration typical of those described above and had an energy consumption of 4,624 kWh and 428 gallons of fuel oil on a per 1,000 ft^2 gross floor area basis (1.79×10^8 J for electricity and fuel oil of .0174 m^3 per m^2 of gross floor area). Using the operating schedules provided by the school custodian personnel, architectural and mechanical data from the blueprints and the weather data for the year 1962-63 for New York City, a thermal energy simulation was performed using the NBS-developed computer program NBSLD. The monthly electrical energy and fuel-oil consumption agreed well with the actual measured energy consumption data. It was also found that 80 percent of electrical energy was used for the lighting of the school building, and 75 percent of useful thermal energy produced by the fuel oil was used for heating ventilation air. It is therefore concluded that the most effective ways of reducing energy consumption for any new school, and also for the existing schools, are to reduce the lighting levels of the classrooms and the ventilation rates (fresh outdoor air). However, these recommendations need to be tempered with study of illumination needs and change in ventilation required by local building codes. The electrical energy consumed by the ventilation fans which comprised 20 percent of the overall electrical energy consumption would be reduced as a consequence of the reduction in the ventilation rate. Since the conduction through the windows and exterior surfaces and infiltration loss comprised 21 percent of the heating energy, improvements in the construction of the building shell will further reduce the overall energy consumption of a new school.

Ventilation tests were conducted for four days in a classroom used primarily by seventh and eighth graders. The purpose of the test was to determine the effects of reduced ventilation on the environment of the classroom, with special emphasis on the CO_2 concentration and O_2 content. It was found that under three different ventilation rates, ranging from 4.6 to 1.3 air changes per hour, the temperature and relative humidity all stayed within the comfort range of 70 to 76 °F (21.4 to 24.8 °C) and 20 to 30 percent. No change in O_2 content was detected, and the CO_2 concentration at the end of a class period in all cases reached a near steady-state level and did not exceed .16 percent by volume, which was far below the safety limit of 0.5 percent established by the Occupational Safety and Health Administration (OSHA). However, when the school building was not ventilated by any mechanical means, the air change rate in the classroom was reduced to only 0.23 per hour. It was estimated that under this condition, the CO_2 concentration level would reach a steady-state level of 0.7 percent by volume, indicating that mechanical ventilation was required to reduce this value to the acceptable level of 0.5 percent or less. The estimate of 0.7 percent CO_2 concentration was based on students in the 12- to 13-year-old age group. It would be higher if the students were of high school age. However, the ventilation test indicates that reduction of the ventilation level from the present 5 air changes per hour to 1 air change per hour would permit the CO_2 concentration or the O_2 content to stay within the established safety limits. The ventilation test of the present study suggests that significant energy savings in new and existing buildings may be achieved by simply reducing the ventilation rates while still maintaining safe and comfortable indoor conditions. A strong need exists to conduct additional ventilation tests of the type reported in the present study for the purpose of supplying needed information to building code officials so that suitable ventilation rates for an energy conserving building can be established.

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Appendix - Calculation of Air Exchange Rates From Tracer Dilution Measurements

Tracer gas is distributed uniformly throughout the ventilated space, and the concentration is measured as a function of time. The rate of decrease of tracer concentration may be represented by the relationship

$$\frac{dc}{dt} = (c_o - c)\frac{v}{V} \tag{1A}$$

where

c = tracer concentration in the space at time t

c_o = tracer concentration in the outside air entering the ventilated space

v = volume rate at which outside air enters the space

V = volume of the ventilated space

In the case of SF_6 tracer gas c_o is usually o, and equation 1A reduces to

$$\frac{dc}{dt} = -c\frac{v}{V} \tag{2A}$$

or

$$\ln\frac{c}{c_i} = -\frac{v}{V}t \tag{3A}$$

where c_i = initial concentration of tracer. If v, V, and t are in consistent units v/V is the infiltration rate in air changes per unit time. Thus, if $\ln(c/c_i)$ is plotted against time, the infiltration rate is obtained from the slope.

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A study was made, under the sponsorship of the National Science Foundation and in collaboration with the New York City Board of Education, of the energy consumption and ventilation requirements of typical existing urban public schools, for the purpose of determining the pattern of energy usage in such public schools so that effective energy conservation measures can be taken both for existing schools and for future new school design.

Electricity and fuel-oil consumption data from May 1970 through April 1973 on 19 existing schools provided by the New York City Board of Education were analyzed. Analysis showed that the overall energy consumption of 17 of the 19 schools varied by a factor of less than 2. Average yearly consumptions per 1,000 ft^2 (92.9 m^2) gross floor area of 5,250 kWh of electrical energy and 417 gallons of No. 6 fuel oil (2.03 x 10^8 J and 0.017 m^3 per m^2 of gross floor area), were selected as a norm typical of the existing schools. These figures correspond to 82,400 Btu/year-(gross) ft^2 (29.7 W/m^2) at the building line or an estimated 126,000 Btu/year-(gross) ft^2 (45.4 W/m^2) when calculated in terms of raw fuel at the generating plant. The figures can be used for future comparison purposes with a new energy conservation school. A computerized thermal energy simulation, using the program NBSLD, was performed on one of the schools having an energy consumption close to the norm. The results showed good agreement between the predicted

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)* CO_2 concentration; computerized thermal simulation; energy conservation in schools; energy consumption; energy utilization in schools; oxygen content; reduced ventilation rate; school operation schedule, ventilation test

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Continuation

and measured monthly electricity and fuel-oil consumption data. Detailed analysis of the pattern of energy consumption showed that 75 percent of the thermal energy during the heating season was used for the heating of outdoor air for ventilation purposes, and 80 percent of the electrical energy was used for lighting.

A ventilation test was conducted over a 4-day period in a typical classroom. It was found that a reduction of the air change rate from the normal 4.6 changes per hour to 1.3 changes per hour did not significantly change the indoor environment as expressed in terms of temperature, relative humidity, oxygen content level, and CO_2 concentration level. However, computation indicates that, when no mechanical ventilation was provided, the CO_2 concentration level would exceed the 0.5 percent safety limit, indicating that natural air infiltration alone will not provide adequate ventilation for the general health and safety of the students.

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